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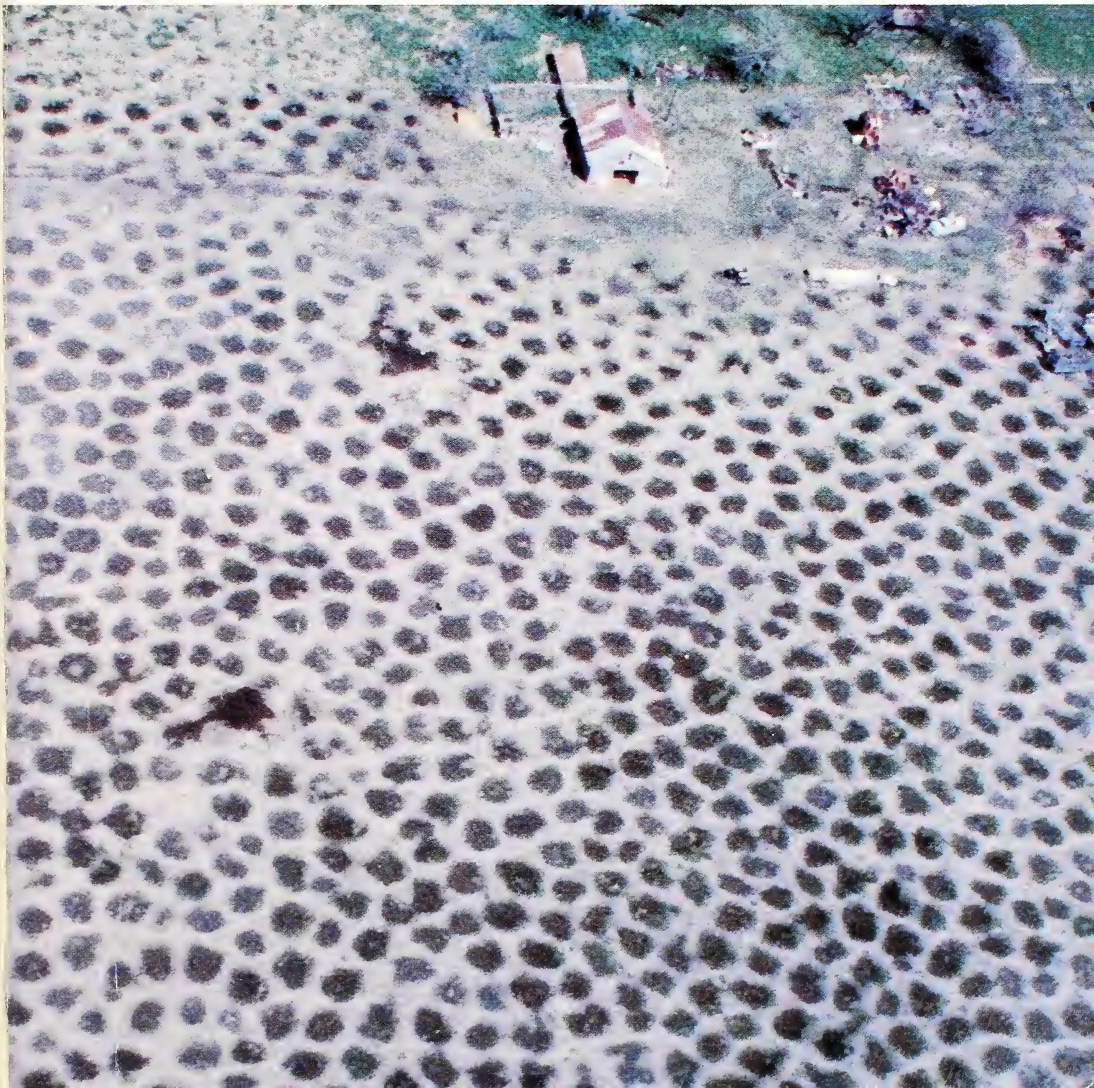
VERTISOLS:

Their Distribution, Properties, Classification and Management

Larry P. Wilding and Ruben Puentes
Editors



COVER:

The colored aerial photograph illustrates gilgai microtopography on a nearly level Wisconsin-age terrace along the Brazos River in Burleson County, Texas. The intricate light and dark pattern corresponds to microrelief elements of the normal gilgai. Dark areas represent more pronounced vegetative cover of microlows that are isolated by interconnected microhigh ridges. Land use is pasture with farmstead buildings in the background (photo courtesy of Dr. T. Hollmark).

NEXT PAGE:

Upper—This photograph illustrates the cyclic horizonation of a Lake Charles series (Typic Pelludert) sampled near Victoria, Texas, on the Beaumont Formation (Late Pleistocene Coastal Plains deposits). Sets of major slickensides outline the lower solum of the microlow (dark area in center) and protrude obliquely towards the microhigh (lighter area to right of photo). Most of slickensides are below vertical zones of cracking. Tape measure is 2m in length. (Photograph is courtesy of Mr. Wesley L. Miller, Soil Scientist, USDA-SCS, Victoria, Texas.)

Lower—This photograph illustrates a close-up view of the above profile crossection at the contact with the microhigh gilgai element. Note the oblique orientation of the sets of slickenside planes which outline the microhigh apex. Tape measure is 1.5 m in length. (Photograph is courtesy of Mr. Wesley L. Miller, Soil Scientist, USDA-SCS, Victoria, Texas.)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Larry P. Wilding and Ruben Puentes
Editors

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Preface

Vertisols comprise important soil resources in many developing and developed countries. However, in extensive regions, they remain underutilized for food production. This happens even in countries with extreme food shortages. Vertisols are generally considered highly productive soils, but they are difficult to manage. Their high smectitic clay content, restricted optimal moisture range for tillage, and high energy demand make them difficult to cultivate; many farmers prefer to concentrate labor inputs on medium and coarse-textured soils, when available.

Following pioneering work by Dudal (Dudal, 1965), Vertisols have been the main subject of numerous international workshops, symposia, seminars, and publications (ISSS, 1982; FAO, 1983; McGarity et al., 1984; Bouma and Raats, 1984; Soil Survey Administration, 1985; Probert et al., 1987; and IBSRAM, 1987). The need to further exchange ideas on Vertisol distribution, properties, classification, and management was the main reason for a symposium held jointly by the American Society of Agronomy and the Soil Science Society of America in Chicago in 1985. It was co-sponsored by the International Agronomy (A-6) and Soil Genesis, Morphology and Classification (S-5) divisions. Dr. F. Calhoun was chairman of the organizing committee. This meeting brought together many scientists from different parts of the world. Most of the papers included in this book were presented at this symposium.

Chapter 1 is an update on the distribution of Vertisols and an introduction to their properties and classification. Ongoing soil surveys have resulted in a significant increase in our knowledge of the worldwide distribution of Vertisols (over 320 millions hectares). These surveys have also shown that Vertisols are not a uniform soil group. That is, their uniform colors and textures belie differences in physical and chemical properties significant to soil management. Chapter 2 is an example of a minimum data set needed for technology transfer to intensify utilization of Vertisols in new regions.

No soil classification system fully integrates all variations in soil properties important to use and management. Chapter 3 analyzes the limitations of Soil Taxonomy and proposes several modifications at different categorical levels for revision of Vertisols. This chapter summarizes several years of activity by the ICOMERT Committee.

Many of the most significant properties from the standpoint of soil management are a direct result of shrink-swell and other pedogenic processes unique to Vertisols and Vertic intergrades. This topic is covered in Chapter 4, which also discusses and compares different models of soil genesis. Shrink-swell properties strongly influence soil water movement and the measurement of soil moisture in Vertisols. Characterizing soil moisture in these soils is still an unfinished challenge but important advances have been obtained, as discussed in Chapter 5.

In agroecological zones which extend from areas of mean annual rainfall of more than 1200 mm to as little as 200 mm, from soil temperature regimes of isohyperthermic to frigid, and under contrasting socioeconomical conditions, farming alternatives are necessarily diverse. Soil management under

such contrasting conditions is discussed in Chapters 6, 7, and 8. In general, most constraints to soil management are determined by soil behavior under alternating dry-wet soil moisture conditions. Nutrients are often assumed to be adequate. However, phosphorous, nitrogen, and micronutrients may be limiting under either low input or intensive farming systems. Chapter 9 specifically discusses P forms, kinetics of reaction, and soil properties which govern P availability to crops. Finally, although slopes are not usually steep, the soil erosion hazard may be high. Soil conservation techniques are discussed in Chapter 10.

While chapters have undergone peer review and editing, scientific content remains the responsibility of respective authors. The editors wish to acknowledge the support received from the Soil Management Support Services for the publication of this book.

L.P. Wilding
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Chapter 1

DISTRIBUTION, PROPERTIES AND CLASSIFICATION OF VERTISOLS

R. Dudal and H. Eswaran

"Democrites states that the best natured soil is the one that takes in rainwater easily, that does not become sticky at the surface, and that does not crack when the rains have ceased. Soils which do not crust as a result of heat are good natured. As a result, says IBN HEDJADJ, to be a good soil it should be neither sticky nor hard. Some have told me, he adds, "How can the wise DEMOCRITES criticize soils that crack since we see that the soils of the territory of Carmona (a city in Andalousia, Spain), which show these features, produce higher yields of wheat than those on soils anywhere else?" So, I say that this soil can be depreciated only in comparison with other soils which are of prime quality according to the principles established above. On the other hand, one should not rank the soils that crack among those of first quality just because they produce good wheat. Since a major part of the seeds and plants entrusted to these soils do not do well, how could we not give preference to other soils. The black soils with a not too dense texture, which resemble old and well-decomposed manure (or earthy layer) and in which all kinds of seeds and plants succeed, should be rated first class on account of its superior quality."

Ibn-Al-Awam
(circa 10th century)

INTRODUCTION

Among the 10 orders of soils recognized in Soil Taxonomy (Soil Survey Staff, 1975), Vertisols are recognized by their propensity to shrink when dried and to swell when moistened. This property is determined by the nature of the soil material, which is characterized by at least 30 percent clay, and the clay itself, which is dominated by a smectitic mineralogy.

Prior to the advent of modern classification systems, soils such as the Vertisols were well known to farmers because of their color, the fact that they produced cracks during the dry season, and, of equal importance, their difficult workability. These soils are sticky clays in the wet season, and are hard in the dry season. It is difficult to cultivate these soils with traditional tools such as the hoe or even a bullock-drawn plow.

Planting dates are well synchronized with a predetermined moisture status of the soil. In many parts of India, planting frequently is done at the end of the rainy season and the crop grows with the stored moisture. Due to their generally favorable fertility status, these soils were sought despite the constraints on their workability.

Vertisols, as defined by Soil Taxonomy, and related soils, are perhaps the only soils group with the greatest number of local, regional, or vernacular names. Dudal (1965) listed about 50 names, some of which are shown in Table 1 along with more recent and more popular Vertisol soil names. Farmers, however, distinguish among the different kinds of Vertisols, as is evidenced in the state of Tamil Nadu, India, where farmers distinguish at least four kinds of Vertisols based on the color and structure of the surface horizons. Hence, such a large number of names affirms the agricultural importance of these soils, particularly in the developing countries.

Table 1. Alternative names for Vertisols. (Not all soils known under these names strictly qualify as Vertisols as defined in Soil Taxonomy. It may be assumed, however, that many do qualify or at least show vertic properties.)

Names	Countries
Names that include the word "black"	
1. Barros pretos	Portugal
2. Black clays	South Africa, Australia
3. Black cotton soils	Africa, India
4. Black cracking clays	Uganda
5. Black earths	Australia, Africa
6. Black turf soils	South Africa
7. Dark clay soils	United States
8. Subtropical black clays	Africa
9. Sols noirs tropicaux	Africa
10. Terra nera	Italy
11. Terres noires tropicales	Africa
12. Terras negras tropicais	Mozambique
13. Tierras negras de Andalucia	Spain
14. Tropical black earths	Angola, Ghana
15. Tropical black clays	Africa
16. Tropical black soils	Africa, India
Names that reflect the black color	
1. Karail	India
2. Melanites	Ghana
3. Teen Suda	Sudan
4. Tropical Chernozems	Africa, India
5. Impact Chernozems	USSR
Vernacular names	
1. Adobe soils	United States, Philippines
2. Badobes	Sudan
3. Dian Pere	French West Africa

Table 1. Alternative names of Vertisols (continued)

Names	Countries
Vernacular names	
4. Gilgai soils	Australia
5. Firki	Nigeria
6. Mbuga	Tanzania
7. Kahamba	Congo
8. Makande	Malawi
9. Morogan	Romania
10. Mourcis	Mali
11. Regur	India
12. Rendzina	United States
13. Shachiang soils	China
14. Smolnitza	Bulgaria, Romania
15. Smonitza	Austria, Yugoslavia
16. Sols de paluds	France
17. Tirs	Morocco, North Africa
18. Vlei grond	South Africa
19. Sonsocuite	Nicaragua
Coined names	
1. Densinigra soils	Angola
2. Gravinigra soils	Angola
3. Grumusols	United States
4. Margalite soils	Indonesia
5. Vertisols	United States

In preparing Soil Taxonomy, the authors first proposed that these soils be named "Tarrasol" from the Greek root meaning "to churn or turn over." However, it was in 1956 that Professor Lehman of the University of Gent Department of Classic Languages proposed the name "Vertisols" from the Latin root with the same meaning (R. Tavernier, personal communication 1985). The nomenclature was first introduced to the scientific community at the Sixth Congress of the International Society of Soil Science (ISSS) held in Paris in 1956. The appropriateness of the term "Vertisol" to such soils is one of the reasons for its wide use in scientific literature. The Food and Agriculture Organization (FAO) adopted the name and definition for one of the classes of soils in the legend of the FAO/UNESCO Soil Map of the World (FAO, 1974). The "Commission de Cooperation Technique en Afrique" (CCTA) also used the reference name in its soil map of Africa (D'Hoore, 1968).

WORLDWIDE DISTRIBUTION

In 1965, the "Dark Clay Soils of Tropical and Subtropical Regions" were estimated to cover 257 million hectares (ha) (Dudal, 1965). Although it was not possible to ascertain whether all these soils matched the definition of Vertisols, it was assumed from available descriptions that a majority of these soils corresponded to the Vertisol concept. "Dark Clays" were found in 76 countries (Table 2), with the largest areas occurring in Australia (70 million ha) (Figure 1a), India (60 million ha) (Figure 1b), and Sudan (40 million ha). Ever since

the first review, ongoing surveys and the preparation of the Soil Map of the World (FAO, 1974) (Figure 2) revealed additional or enlarged extensions of "Dark Clays" in Canada, China, Egypt, Ethiopia, India, Pakistan, Sri Lanka, Sudan, Trinidad, USA, USSR, and Venezuela.

Table 2. Distribution of Dark Clay Soils (after Dudal, 1965).

Countries and Areas	Estimated extent (Million hectares)
Angola; Valleys of the Cunene and Cubango, region of Catete and southwestern part of the country	0.5
Argentina; Mainly in the northeastern part of the country in the province of Entre Rios, inthe northeastern department of Buenos Aires, in south Corrientes, Santa Fe and the Eastern Chaco	6.0
Australia[1]; Mainly in Queensland (Darling Downs), northern Plains), east-central part and coastal areas of the Northern Territories, patches in South Australia (near Adelaide), northwestern Australia and in Tasmania	70.5
Benin; Northern part of the country and in the region of Divo	0.1
Bolivia; Mainly in the eastern part of the country, ngstone and Tuli; probably large areas around the Okovambo and Makarikari swamps	2.0
Botswana; West of Livingstone and Tuli; probably large areas around the Okovambo and Makarikari swamps	0.5
Brazil; Southwestern and western regions of Rio Grande do Sul (Bage, Uruguaiana, Alegrese and D. Pedrito districts); in the western parts of the country bordering Uruguay, Paraguay and Bolivia; in northeastern Brazil.	4.5
Burkina Faso; Souron Valley; poorly-drained basin deposits spread over the country	0.4
Cameroon; Logone Chari basin and part of the Chad Basin; peneplain of Kaele and Marona region	1.2
Chad; Chad basin and scattered patches	16.5
Chile; Depressional areas associated with Non-calcic Brown soils in Santiago and O'Higgins provinces and also associated with Prairie and Chestnut soils in Magallanes Province	0.5
China; Central China	12.0
Ecuador; Hilly lowland and valley bottoms in western part of the country (provinces of Guayas, Manabi, Esmeraldas)	1.0
Egypt; Nile delta	1.0
Ethiopia; Rift valley and Ethiopian plateau	13.0
Ghana; Mainly Accra, Ho-Keta and Wineba Plains; scattered patches near Kpandu, Kwamen and Kwesi	0.2
India; Central and south-central Deccan plateau (parts of Bombay, Hyderabad and Madya Pradesh states)	79.0
Indonesia; Mainly in Central Java (Semarang, Demak, Bodjonegoro, Surabaya area), East Javaand Lesser Sunda Islands (Lombok, Timor, Sumbawa and Flores)	1.8
Ivory Coast; In northern part of the country and in the region of DivoKenya; Athi Plains near Nairobi and other areas	2.8
Lesotho; Drakensberg	2.3

Table 2. Distribution of Dark Clay Soils (continued)

Countries and Areas	Estimated extent (Million hectares)
Madagascar; Some valley depressions in the western part of the country and on uplands in the western and northwestern part	0.8
Malawi; Chyre valley and areas around Nyasa and Chilwa lakes	1.6
Mali; Niger valley, and a large area along the borders with Mauritania	0.7
Morocco; Mainly in the northwest (Gharb) and in the Doukkalas (south of Casablanca); scattered spots	0.2
Mozambique; Alluvial plains of the Limpopo and Inkomati rivers and surrounding uplands; Zambezi valley upstream of Tete	1.1
Namibia; Probable occurrence in the Caprivi Strip along the Cubango river and around the Etosha Pan	0.7
Niger; Central Niger valley and several scattered patches	0.1
Nigeria; Northeast Bornu and Benoue river basin	4.0
Paraguay; Depressional areas in basaltic and limestone plateaus of the eastern region; in the Paraguay river basin and large areas in the Chaco region	1.5
Portugal; Depressional areas on diorite and limestone in Alentejo	0.1
Senegal; Senegal valley, lowland of the northwest	0.2
Somalia; In the plains extending between the Juba and Shebeli rivers	0.8
South Africa; Bush Veld and Springbok Flats (Transvaal), Highveld (Orange Free State and Transvaal)	2.1
Sudan; Region between the White and Blue Nile extending east of the Blue Nile into Ethiopia and covering an area west of the White Nile; widespread in South Sudan, Bahr el Gasal, Upper Nile and Equatoria Province	50.0
Swaziland; Mainly in the Middelveld, eastern Low-veld and Lebombo areas	0.2
Syria; Jezireh and basaltic plateaus south of Damascus	0.6
Tanzania; Valleys of the Mayowosi and Malagarasi, Great Ruaha valley areas near Tendigo swamps and Rukwa lake; scattered upland areas	7.0
Togo; In the northern part of the country and in the Mono valley	0.1
Uganda; Valley of the Semliki, areas near George, Albert and Edward Lakes, areas in the eastand northeast of the country	1.7
Union of Soviet Socialist Republics[2]; Compact chernozems in the Caucasus between Krasnodar and Groznyy	0.8
United States of America; "Blackland" in Central Texas from the Red River bottomland on the north and northeast to the Rio Grande plain in the San Antonio area on the southwest; belt extending from Lowndes Country in Missouri to Perry County in Alabama; basaltic plateaus in Arizona; scattered spots in California, N. Dakota, and Montana; islands of Oahu, Kauai and Molokai in Hawaii	18.0
Upper Volta; Souron Valley, poorly drained deposits spread over the country	0.4
Uruguay; In the southwest, northwest and south central part of the country and along the border with Brazil (Department of Cerro Largo)	1.0
Venezuela	1.5
Zaire; Ruzizi Plain, valleys of the Semliki and Lufira valley	0.3

Table 2. Distribution of Dark Clay Soils (continued)

Countries and Areas	Estimated extent (Million hectares)
Zambia; Valleys of the Luangwa, Lukusashi and Zambezi; Kafue flats	5.0
Zimbabwe; Part of the valley of the Zambezi; Living-stone area and southern part of the country	1.8

Occurrence of dark clays has also been reported from:

Albania, Algeria, Bangladesh, Bulgaria, Burma, Cambodia, Canada, Colombia, Costa Rica, France, Greece, Honduras, Hungary, Iraq, Israel, Italy, Jordan, Mexico, Pakistan, New Caledonia, Nicaragua, Panama, Philippines, Principe, Romania, Sao Tome, Spain, Sri Lanka, Thailand, Trinidad, Tunisia, Turkey, VietNam, Yugoslavia

(The extension of dark clay soils in the respective countries is relatively small and is estimated at about 3.5 million Ha.)

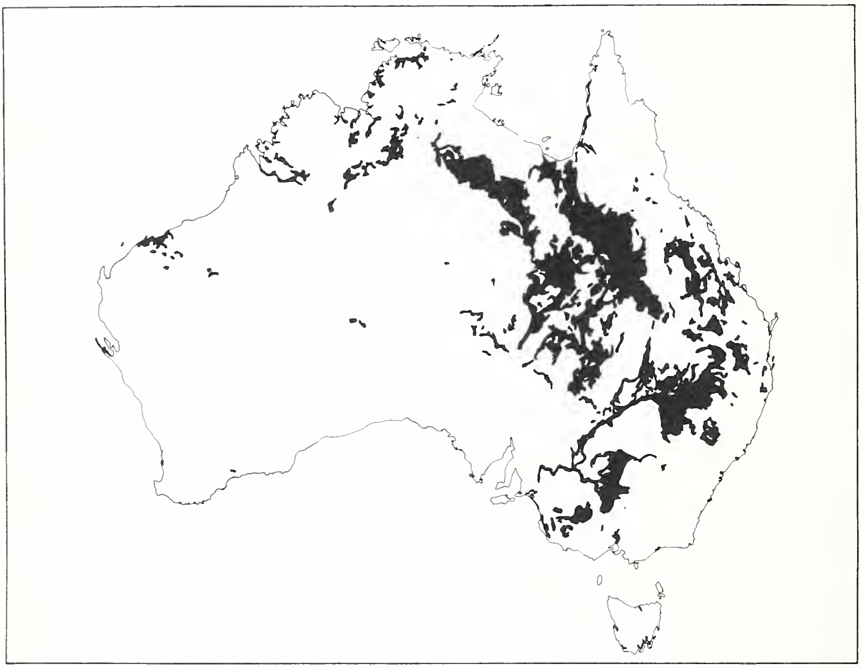

Fig. 1a. Australian distribution of Vertisols and associated soils (adapted from A Soil Map of Australia, in Northcote *et al.* 1975).

[1]The figures available for Australia are 33 million Ha of Black Earths and 75 million Ha of Gray and Brown soils of heavy texture. While Black Earths are probably mainly Vertisols, it is believed that only a part of the latter are Vertisols. The proportion is not known; a figure of 50% of the total area is used here.

[2]The compact Chernozems distinguished in the USSR show distinct characteristics of Vertisols. They are tentatively included here.

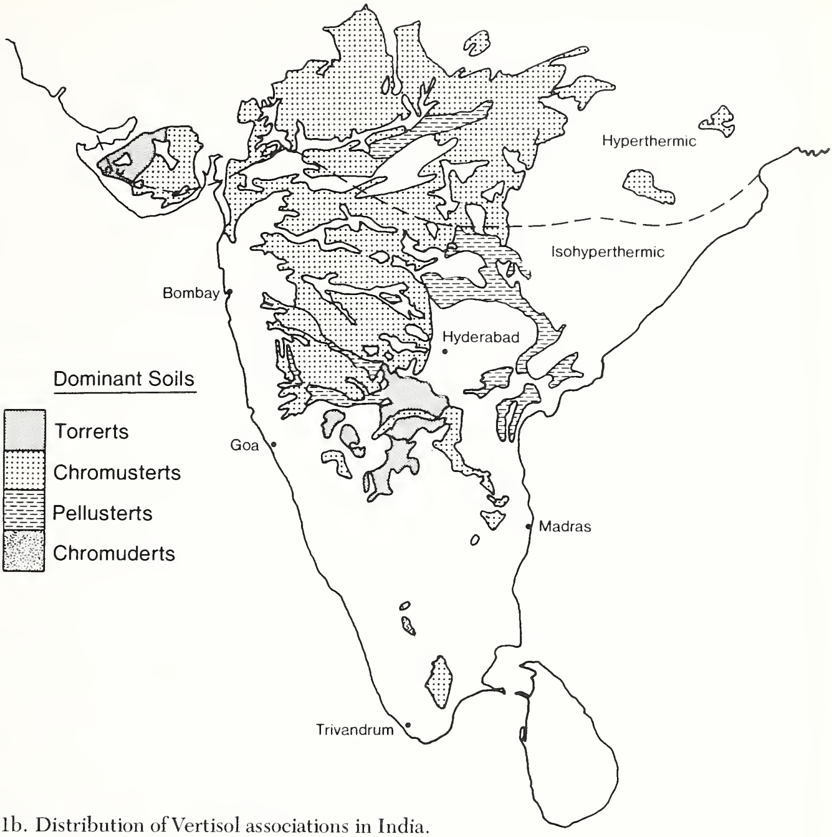

Fig. 1b. Distribution of Vertisol associations in India.

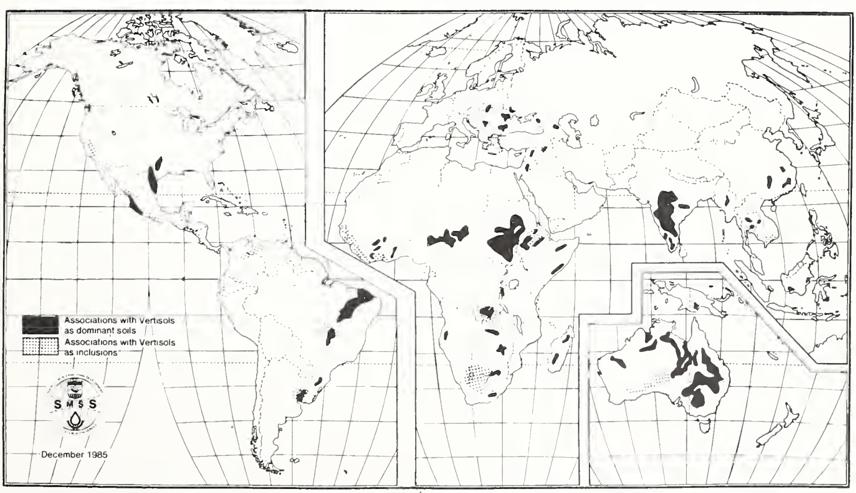

Fig. 2. Soil Associations of Vertisols (Adapted from FAO-UNESCO Soil Map of the World, FAO 1974).

New areas are most important in Egypt (0-1 million ha), Ethiopia (10-13 million ha), India (60-79 million ha), Sudan (40-50 million ha), the USA (5-9 million ha), and Venezuela (1-4.5 million ha). For the United States, the 9 million ha figure would double if Vertic subgroups were included (Nichols, 1985). It now is estimated that on a worldwide scale "Dark Clays" extend over 320 million ha—2.4 percent of a global land area measuring 13.2 billion ha (Figure 2). However, if one deducts permafrosted areas and mountain regions from the total land area, Vertisols occupy a larger portion of the arable or potentially arable lands of the world. It also should be realized that the surfaces mentioned above are not composed entirely of Vertisols in the strictest sense of their definitions. For instance, of the total 79 million ha "black soil region" in India, 28 million ha are considered to be Vertisols, while the remaining surfaces are vertic subgroups of Ustropepts and Ustochrepts (Murthy et al., 1982). The proportion of Vertisols among the "Dark Clays" in Ethiopia, Sudan, and the United States is likely to be much higher. From a management point of view, the vertic subgroups also may present problems similar to the Vertisols and therefore are included in this paper.

It appears that Vertisols, as identified during the last 20 years, are spread over a wide range of temperature regimes—from isohyperthermic near the (60 percent) of the Vertisols occur in the tropical belt, 96 million ha (30 percent) in the subtropics, and only 32 million ha (10 percent) outside the tropical and subtropical regions. Vertisols are estimated to cover nearly 4 percent of the land area in the tropics; hence, they occupy an important place in the developing world.

In ascertaining the extensions of Vertisols in subhumid and humid zones, the soil moisture regimes of Soil Taxonomy (Soil Survey Staff, 1975) have been used. Vertisols having a udic and udi-ustic moisture regime were considered to be humid and subhumid, respectively. The criteria in Soil Taxonomy used to subdivide Vertisols according to moisture regimes are the duration and pattern of soil cracking. In udic Vertisols, cracks do not remain open for more than 90 cumulative days in most of the years, and do not remain open for more than 60 consecutive days during the 90 days following the summer solstice in more than 7 out of 10 years. In some years they may not crack. In udi-ustic Vertisols, cracks close once or more during the year. The cracks are open from 90 to 150 cumulative days in most years but remain closed for 60 or more consecutive days when the soil temperature at a depth of 50 cm was continuously above 8C.

One may wonder if these cracking patterns fully reflect the climatic conditions under which these soils occur, and of which land management and utilization decisions are made. Besides the overall climate, cracking is influenced by the clay content (which in Vertisols ranges from 30-80 percent); the mineralogy of the clay (it appears that Vertisols may crack with as little as 15 percent of smectite in the clay fraction); the composition of the clay fraction (proportion of fine to coarse clay); the saturation of the sorptive complex (Ca, Mg, and Na); the flood hazards; the presence and type of gilgai; and the rainfall pattern. Gilgai may cover 10-70 percent of the land surface. It may be difficult to average the duration of cracking over a certain landscape because cracking is more frequent in the depressions than on the mounds. When the rainy season starts with its heavy downpours, the cracks fill up with water and close.

However, if rain falls in successive, slight showers, only the cracks at the surface close. The resulting slow infiltration may cause cracks in the subsoil to remain open. Vertisols develop their own soil climate; that is, they are drier than the overall climate because of strong evaporation through cracks, and wetter than the rainfall may suggest as a result of waterlogging and a low infiltration rate when the cracks are sealed.

Moisture regimes of Vertisols may be appropriately characterized by the length of the growing period, as defined in the FAO Agroecological Zones Project (FAO, 1978). In humid zones, there are more than 270 days of a growing period that broadly corresponds to the udic moisture regime. The udi-ustic moisture regime corresponds to lengths of growing periods ranging from 210 to 270 days. It is believed that length of growing period from 180 to 210 days, which is partly typic ustic, should be considered as subhumid, otherwise the semi-arid areas might be disproportionately extended. It is beyond the scope of this paper, however, to define limits between semi-arid and subhumid zones. On the basis of the udic and udi-ustic separation, 13 percent of the Vertisol areas occur under subhumid and humid conditions, 65 percent are semi-arid, 18 percent are estimated to be arid, and 4 percent occur in Mediterranean climatic conditions. In each of these zones, however, a common feature characterizes the moisture regime of a Vertisol: a distinct alternation of seasonal wetting and drying conducive to swelling and shrinking.

Attempts have been made to identify the morphological properties that characterize subhumid and humid Vertisols. In Sudan, where Vertisols occur over a wide range of rainfall in level topography and with a relatively uniform parent material, one may observe soil morphological features that vary with the changing climatic conditions (Jewitt et al., 1979; Blokhuis, 1982). With increasing rainfall, proceeding from areas with ustic or xeric soil moisture regimes to an udic soil moisture regime, it is observed that:

a) cracks become deeper and wider;
b) wedge-shaped soil structure appears more distinct;
c) surface mulch weakens and becomes thinner;
d) surface soil crusting occurs more frequently;
e) organic matter in the upper horizons increases and their color becomes darker;
f) soluble salt contents decrease;
g) exchangeable sodium in the sorptive complex decreases or is absent;
h) reliability of rainfall improves;
i) the hazards of flooding increase; and
j) gilgai become more pronounced.

It is not feasible to use these characteristics to differentiate Vertisols in subhumid and humid areas from those occurring in more arid conditions because a number of factors other than climate, such as microtopography, influence the morphology of Vertisols.

The 42 million ha of Vertisols estimated to occur in subhumid and humid areas—13 percent of the global coverage—are located mainly in India (25 million ha), Ethiopia (5 million ha), the United States (3 million ha), Argentina (3 million ha), Venezuela (1.5 million ha), and Indonesia (1 million ha). Vertisols also occur in Brazil, Chad, China, Ghana, Mozambique, Sri Lanka, Thai-

land, Trinidad, and a number of central European countries. It is worth noting that in Australia and Sudan, where large areas of Vertisols occur, only a fraction of these soils are located in subhumid or humid zones.

PEDOMORPHIC PROPERTIES

The morphological properties of a Vertisol are induced by the soil's mineralogical (clay mineralogy) and physicochemical properties, and specific attributes resulting from cyclical variations of the moisture status. The two most critical soil properties are the amount and the type of clay. Gravel and stones, which reduce the effective volume of fine earth, should be present in small amounts. The physical activity of the system increases with the amount of clay if the clay has shrink-swell characteristics. Dominance of smectites and, specifically, of montmorillionite accentuates the volume change characteristics. Other members of the smectite family, such as nontronites and saponites, have a lower equivalent coefficient of linear extensibility (COLE). Organic matter also should be low in such soils to increase the effective volume occupied by the clays. The different kinds of Vertisols are largely due to variations in these properties, coupled with variations in the patterns of the moisture status profile.

Color

Many Vertisols are dark-colored, in spite of a low organic matter content. Complexation or chelation of the organic colloids to smectites probably darkens the mineral. A treatment using hydrogen peroxide oxidizes the organic matter and reverts the soil to its inherent white color; in some Vertisols, however, several treatments may be necessary suggesting other mechanisms rather than a simple complexation. Finely divided manganese oxides also have an intense staining effect resulting in black soils.

Other Vertisols, such as the Chrom Great Groups, are more brownish in color. The absence of black colors is related to smaller amounts of montmorillionites, higher amounts of iron oxyhydrates, better drainage, or a combination of all of these characteristics.

Structure

The structure of Vertisols is almost a temporal characteristic. The size, shape, grade, and consistence of the structural elements are all related to the moisture condition of the horizon at the time the soil is evaluated. The depth at which the different structural elements are expressed is also a function of the moisture conditions in the different parts of the profile. In order to obtain a good appreciation of structure and its evolution, it is necessary to make observations under different moisture conditions. If this is inconvenient, an ideal time for evaluating structure is between a week to a month after the rains. At this period, the upper meter of the soil is at a moisture tension between 0.3 bar and 15 bar, but closer to the latter.

Figures 3 and 4 show an idealized structure profile of five distinct zones or horizons with successive stages of pedogenic evolution.

Zone 1. This zone is from the surface to 25 cm, or to a plow depth subject to cracking and forming large prisms with prism sizes of up to about 30 cm. The material is hard or very hard when dry and the prismatic elements may part to coarse, angular, blocky elements.

Zone 2. Beneath this layer is a 10-30 cm thick zone with hard to very hard, coarse, angular, blocky elements; sometimes aggregations of these elements may develop into discernable prisms. If it underlies a plow layer, this compact zone might create restrictions to root penetration.

Zone 3. The thickness varies from less than 10 cm to more than 1 m thick, where it grades to Zone 5 without the intervening Zone 4. Soil Taxonomy refers to the structural elements in this third zone as "wedge-shaped natural structural aggregates that have their long axis tilted 10 to 60 from the horizontal." These structural aggregates have an orthorhombic form; are generally 5-10 cm along their long axis; and have ped faces that are smooth or striated with the stria generally in subparallel lines to the long axis. Their mode of formation is related to the slickensides, which are characteristic of Zone 4 but with much larger features.

Zone 4. This is the zone of slickensides and measures 25 cm to 1 m thick. The term "slickenside" refers to a surface that has a polished and shiny appearance and that also may be striated or grooved. The term does not refer to a structural element, which is a three-dimensional entity. However, a slickenside form the surfaces of the wedge-shaped aggregates described earlier, but in this zone are larger—measuring 600 to 2000 cm^2 in area. Its surface topography is not flat; rather, it is curved or even slightly undulating. Slickensides occur in subparallel sets with the long axis of each set tilted from the horizontal, giving the impression of intersection. The net result of the inclined nature is to produce a set of intersecting slickensides arranged in a synclinal form.

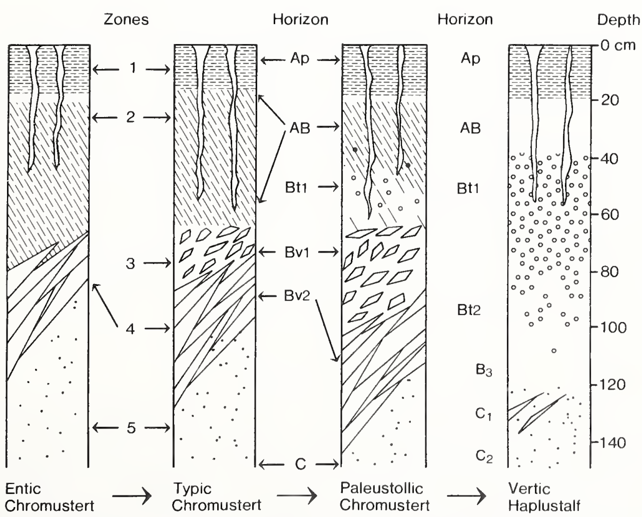

Fig. 3. Morphological differentiation of a sequence of soils (generalized).

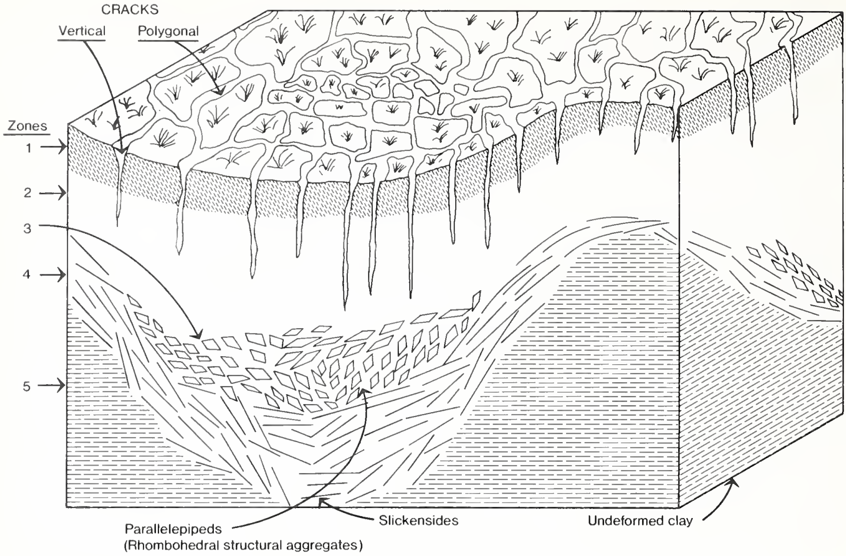

Fig. 4. Cross section of gilgai micro-relief.

The deepest part of the syncline is between 50 cm to 1.25 m, while the shallower arms are at about 25-50 cm, reaching the plow layer. The amplitude of the two arms is the diameter of the gilgai and may vary from about 3 m to more than 25 m. The thickness and degree of expression of zones 2 and 3 are a function of the depth at which the arms of the slickenside synclines approach the surface.

Zone 5. This zone consists of the clay and underlies Zone 4 or is directly below Zone 3. This layer is subject to only slight moisture variations; it is massive and may show accumulations of gypsum and carbonates.

Although the degrees of expression for Zones 2, 3, and 4 may vary with fluctuations of moisture content, their relative positions in the profile are relatively constant. This may be inferred from the position of any associated iron-manganese, lime, or gypsum concretions, which are not randomly distributed as would be expected if the zones shifted position seasonally. Further, in some soils these concretions or nodules also show a synclinal distribution pattern. However, pedoturbation processes may produce observed fragmentation of the concretions and slight lateral displacement.

Variations from the model profile is the rule rather than the exception (Figure 5). One or more of Zones 2, 3, or 4 may be absent. Conceptually, either Zone 3, 4, or both must be present to identify the soils as Vertisols.

Cracking Pattern

The development of cracks is induced by the drying of wet soil, which causes the material to shrink. Cracks may be obliterated by subsequent cultural activities, but those below the plow zone continue to exist. The cracks penetrate to more than 50 cm and generally terminate at Zone 3 or 4 if the

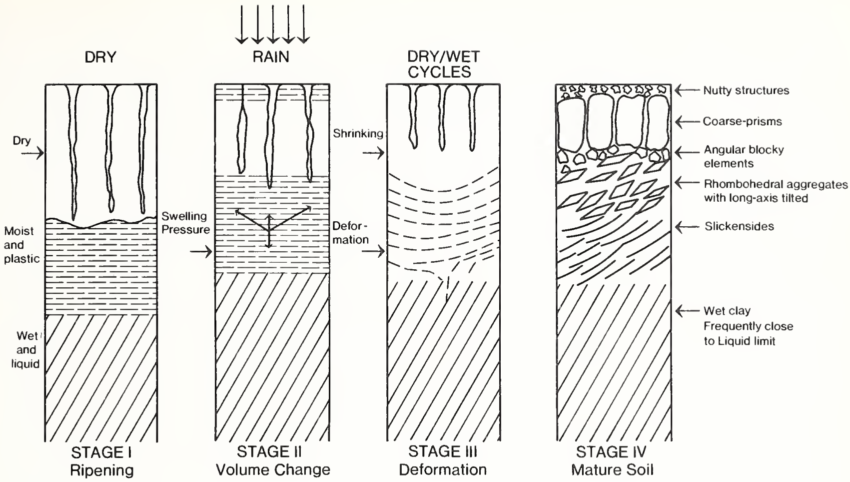

Fig. 5. Morphological changes associated with Vertisol formation.

former is not well expressed. The cracks are wide but tortuous and, by definition, must be at least 1 cm wide at a 50 cm depth.

The formation of cracks is not merely a response of the material to dehydration; rather, the differential moisture status of the zones plays a role in determining the depth of cracking, the frequency of the cracks, and the size and shape of the cracks. The cracking pattern also is influenced by remoistening after the first-generation cracks are established.

A function of the wetting process is to close the cracks. Slow, intermittent rain causes the water to penetrate the cracks, and moistening begins from Zone 3 or 4 and continues upwards. Short, high-intensity rains may cause the upper part of the soil to moisten rapidly, and the cracks in the top 5 cm may close up and effectively seal the soil. Due to a very low hydraulic conductivity, further wetting is a slow process and subsoil cracks take much longer to close.

When cracks are open to the surface, soil materials fall in. When the pedon is homogeneous with respect to color and texture, the in-filled material is incorporated into the subsoil material during the subsequent pedoturbations and no evidence of the in-filling may be seen. However, if the surface material is of coarser texture, the in-filled material is entrapped and the vertical streaks identify to the in-filling. are present in the center of the polygons. The rhizosphere of the clumps presents a slightly moister environment compared to the nearby area where cracking begins.

Surface Nutty Structures

In highly clayey soils and where the clay is almost completely composed of montmorillionite, the 2-5 cm surface develops into a fine, angular, blocky, structural element that has been described as nutty structures. During the dry season, these structural elements, which may be very hard, appear as loose gravel strewn on the surface. The term "Grumosols" was used for those Vertisols which exhibited this feature.

Clay Translocation

With a smectitic clay that has finer particle size and a higher surface charge, dispersion, translocation, and accumulation should not be a problem if other factors are conducive to such processes. The processes and conditions governing formation of clay-skins or cutans have been elaborated by Eswaran and Sys (1979), and in most Vertisols these processes are nonoperative or the consequences are obliterated by the pedoturbation processes.

The fact that clay can and does move in some Vertisols is illustrated by the presence of cutans in Zone 5 which is subject to the least amount of pedoturbation (unpublished micromorphological data of second author). However, the amount of cutans is not enough to suggest a significant pedogenetic process. In some soils, evidence of translocated clay accumulation may be established in Zone 2. In such soils, the surface horizons are leached and have a pH lower than 6.5. With advance of leaching and accumulation of translocated clay to form an argillic horizon, the soils evolve into Alfisols and are, for example, Vertic Haplustalfs (Figure 3). This is one mode of formation of such soils. In another instance, the soils belong to the Paleustollic Chromusterts (Figure 3) when clay-skins are evident but the horizon does not qualify as being argillic.

MICROVARIABILITY

As previously indicated, structure formation is due to differential moisture stress. The moisture stress varies from point to point both vertically and horizontally. The shearing forces within the soil is reflected on the surface micro-topography as subcircular depressions rimmed by ridges. Such features are termed "gilgai" by Australian pedologists and was introduced by Prescott (1931). Hallsworth et al. (1955) and Harris (1959) identified several kinds of gilgai:

- Round gilgai
- Mushroom gilgai
- Tank gilgai
- Wavy gilgai
- Lattice gilgai
- Depression gilgai

The different kinds are identified by the shape of the depression, or the size and shape of the depression in relation to the ridges. The most frequent form of these is the round gilgai.

The gilgai micro-relief may not be very evident in all Vertisol areas. Continuous cultivation tends to destroy the micro-relief. In other areas, particularly where there is a textural gradation with depth, the micro-relief is not evident even in uncultivated areas.

Hallsworth et al. (1955) and Edelman and Brinkman (1962) have attempted to explain the development of gilgai. The latter related the strength of the underlying wet clay as a shearing force which is introduced causing the soil material to be sheared at an angle of 30-50° from the horizontal, and resulting in the formation of slickensides. Slickensides can only form when the material is plastic, which denotes the deformation zone in Stage III (Figure 5). Above this zone the soil material is dry; below the soil material is too close to the liquid limit. However, just at the upper limit of the deformation zone the soil

is close enough to the plastic limit to be subject to some deformation. Shearing does not take place here. Structural elements (rhombohedral aggregates) form but also are tilted 30-50° from the horizontal as they become subjected to some pressure.

The shrink-swell changes also are experienced in the upper part of the profile and the resulting structural forms depend on the frequency of and the forces acting on the material. Since this zone is close to the surface, changes in the moisture state are rapid and the impressed forces are less, forming only coarse prisms in most situations. The various structural types characterize Stage IV (Figure 5), which is the morphology of the mature Vertisol.

The above processes and forces operate over a large area. The slickensides are tilted, and on a horizontal section a synclinorium of slickensides form a "bow-structure," a process by which a ripening of the sediment with a concomitant change in volume results in deep, broad cracks that are in-filled. The process is related to cyclic heaving. Hallsworth et al. (1955) attributed it to expansion of moistened clay, where lateral pressures are developed and can only be released by an upwards expansion initiating a mound.

There is no simple explanation; in order to explain the gilgai, the soil has to be considered as an interacting system. The morphological features mentioned earlier and the micro-relief characteristics are related, showing the consequence of different forces acting upon the soil. To understand the processes, one has to visualize a model. First, consider the situation where the soil to a certain depth is dry or close to a 15 bar tension; beneath this, the soil is moist and the material is plastic. This is illustrated in Stage I (Figure 5). Lowering the water table accentuates the ripening process and permits the upper part of the soil to dry out; shrinking the upper part forms cracks. With a subsequent rain, the cracks conduct water directly to the lower part of the dry soil, causing this part of the soil to swell preferentially.

The swelling pressure (Stage II, Figure 5) is exerted in all directions and causes deformation of the plastic clay. The soil load retards an upward movement and is dependent upon the characteristic feature of many or most Vertisols. The slickensides are thickest in the lowest part of the profile (Figures 4, 6, 7) and thin out as they approach the soil surface. In some soils, two adjoining gilgai might have overlapping slickensides forming an anticlinorium at this contact point. In others, the ridge may be free of slickensides.

The rhomobohedral structural aggregates follow the same pattern as the slickensides (Figure 4). These suggest that the gilgai formation is related to the formation of the slickensides and the structural aggregates. The surface cracking aids in the formation of the whole set of features.

This particular morphology of Vertisols presents problems in characterization, sampling, and classification. As the ridges may be 2-3 m broad, pits of this width or smaller that are dug on the ridges (which may be imperceptible on the soil surface) will lead to a wrong classification.

Generally, the ridges are better and more easily drained than the depressions. Microvariability of crop performance is sometimes very distinct. When the land is leveled for agronomic experiments, though the surface micro-relief is erased, the subsoil variability can affect crop performance, introducing tremendous errors in field experimentation.

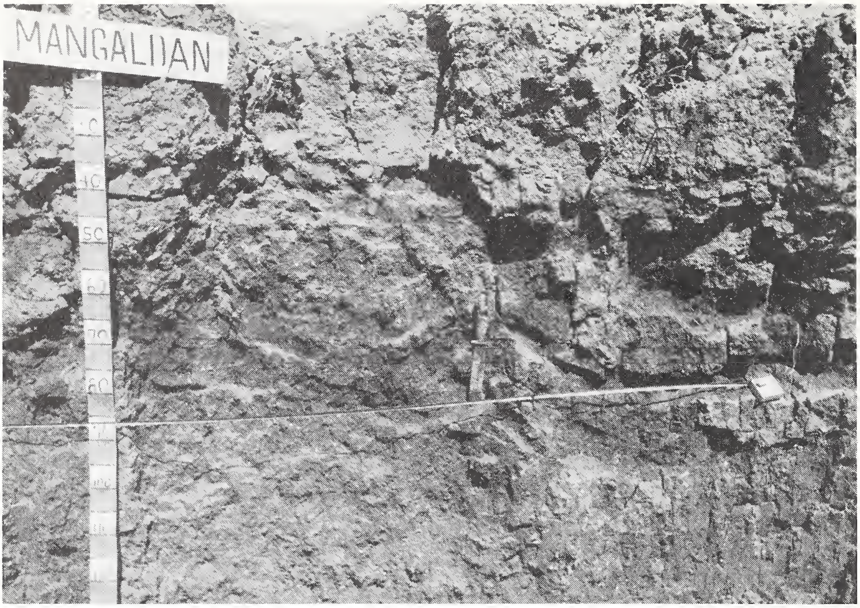

Fig. 6. A Pellustert from the Phillippines. Synclinal arrangement of slickensides is clear. The measurements are in cm.

Fig. 7. Close-up of Pellustert (Figure 6) showing arrangement of slickensides.

LANDSCAPE RELATIONSHIPS

The most frequent physiographic position for Vertisols is flat alluvial plains, sometimes subject to a fluctuating water table. Good examples are the clay plains of Sudan, the Houston Black clays in Texas, and the heavy-textured cracking clays of the Darling Downs in Australia. On these plains, the only relief is that produced by gilgai, if the gilgai themselves are present; otherwise, the plains are flat. Similar physiographic positions are exhibited in the narrower valleys, such as the Lufira Valley of Zaire and the Kafue Flats of Zambia. Even on these plains or flats, depositional differences in the alluvium result in differences in the soils. On the Ruzizi plain in Burundi, the Pellusterts occur in association with Natrustalfs and some Albaqualfs. On the clay plains of Sudan, it is common to find reddish Rhodustalfs on more coarser-textured knolls.

The Deccan Plateau in India presents a different situation, where the soil is derived from weathering in situ of the basaltic rocks. The present-day physiography is partly determined by the original topography of the basaltic rock. The depth to rock becomes an important determining factor in the nature of the profiles. A section from the summit position to the flats is composed of the following kinds of soils: Lithic Vertic Ustochrepts, Vertic Ustochrepts, Entic Chromusterts, and Typic Chromusterts. In central India where the basement complex rocks come to the surface, alluvial-colluvial interfingering of the black Pellusterts with the reddish Rhodustalfs-Haplustalfs give rise to the classical red and black soils described in Indian literature. The Vertisols occupy the depressions; the Alfisols, the upland position.

In Southeast Asia, the coastal alluvial plains are composed of an association of Aquepts, Aquents, and Vertisols. In the Kedah Plains of Northwest Malaysia, pockets of Chromuderts occur in association with Sulfaquepts and Haplaquepts. The Vertisols are better drained than the other soils, but as the soils are irrigated in the off-season for padi their tendency to crack lessens. On the coastal plains of Luzon in the Philippines, Chromusterts occur in association with Haplaquepts and Vertic Haplustolls.

A topographic sequence in central Java in Indonesia is illustrated in Figure 8. On the upper slopes of the volcanoes, Andepts (Andisols) are present; on the undulating upper slope position, Eutropepts and Hapludalfs are common; on the flat, lower slope positions, Paleustalfs may be seen. In the valley bottoms, Chromusterts with associated Vertic Haplaqualfs are present.

Another sequence observed in Papua New Guinea consists of a Lithic Ustropept on a hill, with a Lithic Haplustalf on the slope. When the slope is less than 10 percent, the soils are Typic Natrustalf giving way to a Vertic Natrustalf on the lower part; in the depression, a Typic Pellustert with a saline phase prevails.

In the Mediterranean areas, large areas of Vertisols are associated with basalts or limestones. The classical Tirs of Morocco are Pelloxererts. In Tunisia, the contiguous extent of the Vertisols is much smaller. Typically, the Pelloxererts occupy the valley bottom and grade to Chromoxererts and Lithic Xerochrepts on adjacent upper slopes. In some areas the Vertisols occur in association with Haploxerolls.

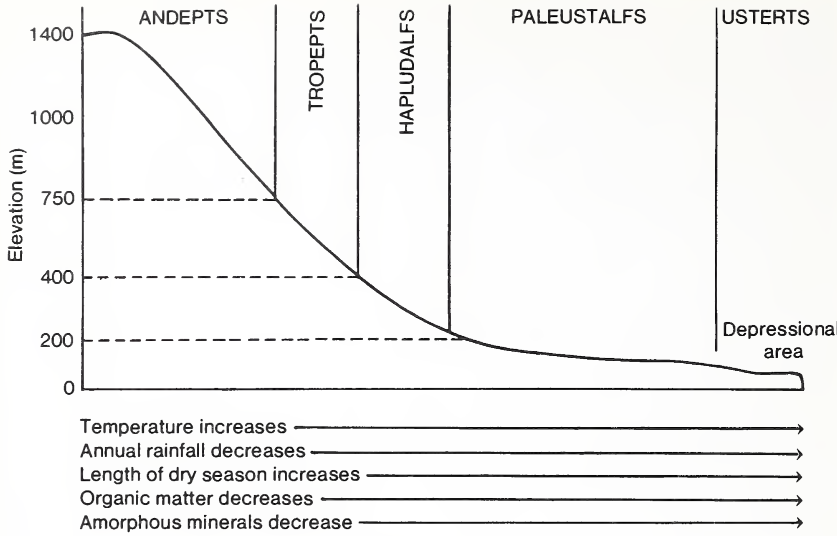

Fig. 8. Soil associations along the slope and base of a volcano in Central Java (Indonesia). Soils developed from volcanic ash and of mudflows on the lower slopes are of uniform age. *Source:* Adapted from Dudal and Soepraptohardjo (1960).

Marked changes in color as a function of the physiographic position is common as shown in Figure 9. The depressional Vertisols (Association A in Figure 9) are always darker, as evidenced in the Pelloxererts, than the slope Vertisols which are the Chromoxererts. The effective soil volume is much lower due to the presence of a petrocalcic horizon within 1 m.

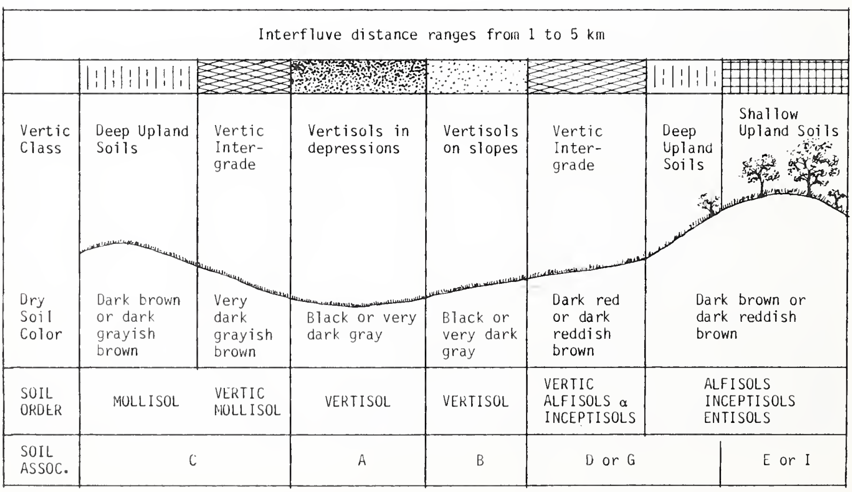

Fig. 9. Schematic showing general pattern of soil distribution in cross section (*Source:* Fenger, Hignett, and Green 1982).

CLASSIFICATION

The properties used in the classification of Vertisols are those unique to this class of soils and some that are shared with other soils. Earlier systems placed emphasis on the cracking properties, but many soils, particularly the heavy clays, crack when they are subjected to moisture tensions greater than 15 bar for prolonged periods. Consequently, cracking by itself is not a differentiating characteristic. The concept of the Order of Vertisols is sufficiently narrow to include only a small group of the cracking soils.

Order criteria

The order is defined by the following:

1. Do not have a lithic or paralithic contact, or petrocalcic horizon, or duripan within 50 cm of the surface; and
2. After the soil to a depth of 18 cm has been mixed, as by 30% or more clay in all subhorizons to a depth of 50 cm or 50 cm that are at least 1 cm wide and extend upward to the surface or to the base of the plow layer or surface crust; and
3. Have, at some time in most years unless irrigated or cultivated, open cracks at a depth of 50 cm that are at least 1 cm wide and extend upward to the surface or to the base of the plow layer or surface crust; and
4. Have one or more of the following:
   a. Gilgai;
   b. At some depth between 25 cm and 1 m, slickensides close enough to intersect; or
   c. At some depth between 25 cm and 1 m, wedge-shaped natural structural aggregates that have their long axis tilted 10 to 60° from the horizontal.

The first requirement essentially provides for a deep soil or at least one that does not have a root-restricting layer within 50 cm. Sufficient depth is necessary to develop the full expression of the vertic attributes; if this effective depth is absent, the soils are placed in vertic subgroups of other soils. In addition to the depth, the second criteria requires more than 30 percent clay in all subhorizons to a depth of 50 cm. A thin layer of coarser-textured material is permitted in the soil surface; however, when it is mixed to a 18 cm depth there should be at least 30 percent clay.

Vertisols, fourth in the Key to Soil Orders (Soil Survey Staff, 1975), is placed after the Histosols, Spodosols, and Oxisols; consequently, they do not have the properties definitive of these soils. Because the Oxisols are keyed out earlier, Vertisols have a cation exchange capacity (CEC) higher than 16 meq per 100 g clay.

The inclusion of item 3 in the Vertisol definition requires them to have cracks that deeply penetrate the soil and are at least 1 cm wide at a depth of 50 cm. The term "open crack" is interpreted to be a separation between gross polyhedrons. If the surface horizons are strongly self-mulching—that is, if the

soil is a mass of loose granules—or if the soil is cultivated while the cracks are open, the cracks may be largely filled with granular materials from the surface. They are considered to be open in the sense that the polyhedrons are separated.

In addition to the depth, clay content and cracks, Item 4 requires Vertisols to have either gilgai, intersecting slickensides, or the natural structural aggregates. A model Vertisol will have all three characteristics, although Vertisols portraying just one or two of these properties also are common.

Suborder criteria

The suborders are defined on the period or periods the cracks remain open or close; the intent is that cracking dynamics will parallel the soil moisture regime definitions. In practice, an estimate of the period the cracks remain open can be made from the length of the dry period, which introduces a degree of subjectivity in the classification that is unavoidable.

The period during which the soil exhibits shrinking and swelling is controlled by the fluctuations of the soil moisture regime and consequently, soil moisture regimes are employed to define taxa at suborder levels. The presence of an aquic moisture regime is not provided, due to the fact that such soils in Venezuela and parts of Southeast Asia, and a suborder of Aquerts has been proposed.

Great group criteria

Only two great groups are provided for in each suborder: the dark soils known as 'Pell' Great Group, and the more brownish or reddish soils known as the 'Chrom' Great Group. A chroma of 1.5 differentiates the two. The reason for the dark colors is not established and is probably related to the amount of smectites, clay, organic matter and the period of moisture saturation. Finely divided manganese contributes to the dark colors while, finely divided lime can lighten the color. Although the two soil great groups are morphologically distinct, little else can be said of their performance-related characteristics. There are suggestions to consider other properties to define new great groups. For example, there are Vertisols with high aluminum saturation, high salinity, or high alkalinity. Vertisols with calcic, petrocalcic, gypsic, and even argillic horizons have been reported. These are morphogenetic properties suitable for recognizing great groups. Although such soils have been described, less is known of their worldwide extent.

Subgroup criteria

There are few subgroups provided for in Vertisols and they mainly relate to the color, or to the presence or absence of ped coatings in the surface horizons. The current subgroups are inadequate and perhaps incomplete and an International Committee on classification of Vertisols is working to improve the classification of these soils.

CONCLUSION

It is estimated that Vertisols cover about 320 million hectares (ha) of the world's land area, and were developed under a wide range of temperature and moisture regimes. Of their total surface, 60 percent occur in the tropics, 30 percent in the subtropics, and 10 percent outside the tropical-subtropical belt. In subhumid and humid zones, they represent 13 percent of the global coverage; 65 percent occur in semi-arid areas, 18 percent in arid areas, and 4 percent under Mediterranean conditions. Vertisols show characteristics that are related to the overall climate; however, other factors such as texture, clay mineralogy, the nature of cation saturation, and the amount of exchangeable sodium have an equally important influence on soil morphology so that a correlation with climate is difficult to establish. Vertisols have been put to a wide range of land use. They offer considerable potential for the expansion and intensification of agriculture, subject to the application of technologies that are designed to meet the specific Vertisol management requirements.

The Vertisol definition stresses cracking, pedoturbation, and movement within the soil mass (slickensides). It should be noted, however, that from the viewpoint of management other characteristics appear to be more important: hardness when dry, plasticity when wet, very low infiltration rate when the surface soil is sealed, very slow saturated hydraulic conductivity, compaction as a result of swelling, available water capacity, presence or absence of surface mulch, sodium saturation, possible salt content, rooting volume, and occurrence of permeable materials in the subsoil.

It is imperative that these characteristics be taken into account, if not in soil classification then at least for technical assessments aimed at evaluating the potential of these soils and at determining management practices. In the development stages of Soil Taxonomy, a distinction was made at the great group level between "grumic" Vertisols that develop a loose, porous, surface mulch of discrete, very hard aggregates and those—the "mazic" ones—that on the contrary develop a platy or massive surface crust with an uncoated silt or sand grains which persist after drying. Subsequently, this differentiation was abandoned as it seemed to be influenced more by management and to vary from one year to another. In humid areas, however, the crusting phenomenon seems to be more frequent and is of importance for the water regime of the soils concerned: less water intake, more hazards of waterlogging, difficult tillage, and poor seed bed conditions. The relationships between crusting in Vertisols and other soil-forming factors point an intergrading toward Planosols (Dudal, 1973). In fact, where these soils are not plowed a thin albic horizon overlying heavy clay may be found.

While Vertisols make up a relatively homogeneous order in a taxonomic sense, it should be stressed that they show a great diversity in characteristics that are of paramount importance to their wetting, drying, and suitability for plant growth. The effectiveness of precipitation on Vertisols is strongly influenced by factors that determine water entry, water retention, and water removal (when it occurs in excess of uptake capacity). The latter factor is of particular importance in subhumid and humid zones with special reference to tillage operations and soil aeration during the growing period.

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Chapter 2

VERTISOLS OF CENTRAL BURMA

F. G. Calhoun , J. M. Bigham , and N. E. Smeck

INTRODUCTION

Vertisols are not extensive in Burma but they do represent an important soil resource in the central "Dry Zone" (Fig. 1). This region of ustic soil moisture regimes is characterized by a 4-5 month rainy season with mean annual precipitation ranging from 500-1200mm. This is also the most important vegetable oil production (groundnut, sesame, and sunflower) region of the country.

The primary objective of this study is to provide the first detailed information on field morphology; chemical, physical, and mineralogical characterization; classification; and genesis of the Vertisols of Burma. The three pedons described here are believed to be representative of the approximately 678,000 hectares of Vertisols and associated soils occurring in central Burma (FAO-UNESCO, 1977).

DESCRIPTION OF THE STUDY AREA

The central Burma "Dry Zone" extends from 18°-23° north latitude and from 94°-96° east longitude. It is bounded on the west by the Shan Hills (Sino-Burman Ranges) which are primarily limestone and on the east by the Chin Hills which are part of the Indo-Burman Range (Bender, 1983). The climate is predominantly arid according to the Thornthwaite classification (Huke, 1982); however, the soil moisture regimes are mostly weak aridic, aridic tropustic, typic tropustic and typic tempustic (Van Wambeke, 1985). The N-S mountain ranges are effective barriers for the SW monsoon; thus, the central part of the Inner-Burman Tertiary Basin lies in a rain shadow during the summer monsoon (Bender, 1983).

Much of the natural vegetation of the zone has been destroyed by farming. Where the original flora still exists, it consists of a scrubby growth of small

trees (*Acacia spp.* and *Euphorbia spp.*), cacti and short grasses. In moving to the higher rainfall areas on the perimeter of the zone one encounters an open tropical savanna composed of grasses and deciduous trees .

Three Vertisol pedons (designated Bu-4, -7, and -9) were investigated at the Myananda Agricultural Research Station, Chaungmagyi Seed Farm and Sebin Seed Farm, respectively (Fig. 1). The Myananda sampling site (Bu-4) was a lakebed during historical times (late 1800s); thus, the parent material is considered to be lacustrine clays and silts. The Chaungmagyi (Bu-7) and Sebin (Bu-9) sampling sites occur on lower topographic positions close to ephemeral streams and have developed from clayey alluvium. Associated soils in the landscape for both the latter sites include Ustifluvents, Haplustalfs, and Ustropepts.

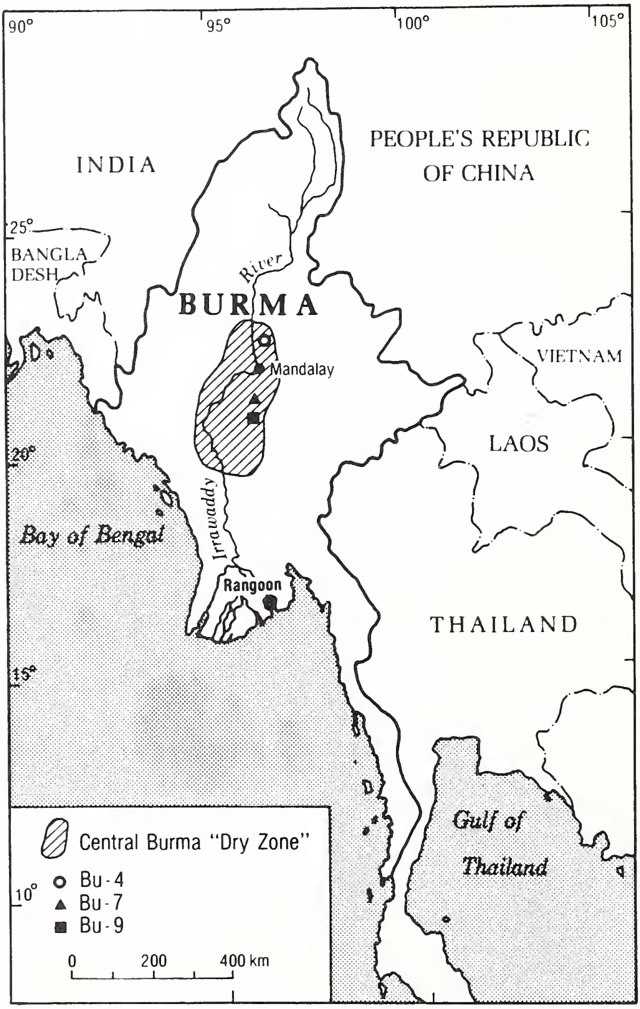

Fig. 1. Location of Vertisol pedons sampled and central "Dry Zone" of Burma.

Traditionally the Vertisols at all three locations have been cropped to paddy during the rainy season followed by cotton or an oilseed crop on residual soil moisture or are left fallow. Irrigation water is readily available at Myananda and for some of the Vertisol locations south of Meiktila.

MATERIALS AND METHODS

A pit approximately 1.5 m deep was dug by hand for each pedon and soil morphology was described using the nomenclature of the Soil Survey Staff (1981). Bulk soil samples were dried at 60°C, crushed using wooden rollers, passed through a 2-mm sieve, and thoroughly mixed. The coarse fragment content was determined by weighing the >2-mm fraction.

Particle-size distribution was determined using the pipet method of Kilmer and Alexander (1949) following dispersion with sodium hexametaphosphate [$Na(PO_3)_6$] and without any pretreatment for organic matter removal. Soil pH in water and 0.01 M $CaCl_2$ was measured following equilibration for 1h using a soil volume to solution volume ratio of 1:1 and 1:2, respectively. Organic C content was determined by dry combustion at 950°C according to the method of Nelson and Sommers (1982). Calcite and dolomite contents were determined by the gasometric method of Dreimanis (1962) employing a Chittick apparatus, and $CaCO_3$ equivalents were calculated from the results. Cation exchange capacity (CEC) was determined by NH_4OAc extraction at pH 7.0. Free iron and manganese oxides were extracted with a sodium citrate-sodium dithionite solution. Iron and manganese in solution were subsequently measured using atomic absorption spectrometry.

For mineralogical analysis, thirty-gram subsamples were separated into sand (2000-50μm), silt (50-2μm), and clay (<2m) using standard sieve and gravity sedimentation techniques (Jackson, 1975; Rutledge et al., 1967). Prior to fractionation, carbonates were dissolved with a 1M acetic acid-sodium acetate buffer (pH 5) and organic compounds were removed with H_2O_2. The isolated clays were Mg-saturated, washed with deionized water to remove excess salt, and freeze-dried.

Total K in the <2μm-materials was determined by atomic absorption analysis following complete dissolution of the samples in a teflon-lined acid digestion bomb using the method of Bernas (1968). Clay mineralogy data were obtained by X-ray diffraction analysis of 30-mg samples of clay oriented on 25 × 75 mm glass slides. All specimens were X-rayed using CuKα radiation with a diffraction assembly that included a theta-compensating slit, a 0.2 mm receiving slit, and a diffracted beam monochromator. Standard chemical (Mg-saturation, K-saturation, water, and glycerol solvation) and thermal pretreatments (25, 350, and 550°C) were employed in all cases.

RESULTS AND DISCUSSION

Morphological Characteristics

Each of the three pedons displays most of the traditional characteristics of Vertisols in other parts of the tropical world (Appendix). Noteworthy for its

absence is gilgai microrelief. A primary reason for the lack of gilgai may be the fact these soils have been cropped to paddy for many, if not hundreds, of years. Under this cropping system the soil surface would have been puddled annually and remained under water for several months during each monsoon. This process would result in only one wetting/drying cycle each year and effectively diminish the thrust forces responsible for gilgai formation. The annual process of puddling, leveling, and bund reformation would likewise work to neutralize microrelief. Puddling also explains the lack of strong granular structure in the surface horizons of two of these soils.

Based on observations by the senior author during the latter part of the 1985/86 dry season, the Burma Vertisols form cracks both wide and deep enough to meet the criteria for the order placement. Slickenside expression is not as strong as that in temperate regions nor in tropical regions where paddy is not the primary agricultural use. Another possible theory to explain weaker slickenside development is the fact that most ustic soil moisture regimes in the tropics usually have only one wet/dry cycle per year while tempustic Vertisols may have two or more per annum.

The Pyawbwe (Bu-7) and Yamethin (Bu-9) pedons showed evidence of infilling of cracks during the beginning of the rainy season. These pedotubules generally showed maximum expression between 50 and 125cm in depth. A lack of these pockets and streaks in the Myananda (Bu-4) pedon may indicate that it has had a shorter cultivation history if, in fact, the site was a shallow lake during the time of the Burmese kings.

The three Vertisol pedons described here were observed during the monsoon when Vertisol structure is not well expressed due to the higher levels of soil moisture. Dudal and Eswaran (1988) suggest that the ideal time for evaluating structure is between a week to a month after the rains. Each of these pedons express to some degree at least three of the first four idealized structure profile zones described by Dudal and Eswaran (1988). Zone 5 (massive clay) was not identified simply because the pedons were not investigated to sufficient depth.

Zone 1 is well-expressed in all three soils although due to the relatively moist state the prismatic nature of the zone was not evident. Zone 2 was not well-expressed in the Yamethin and Pyawbwe pedons. This zone was best expressed in the Myananda profile by the extremely hard, coarse and very coarse angular blocky structure of the Bw1 horizon. Zone 3 was poorly developed to nonexistent in all three soils. This was most likely the result of high soil moisture contents since the descriptions were made during the monsoon. Zone 4 was only moderately expressed in the Bu-7 and -9 pedons and was weakly developed in Bu-4 because of a shorter time span for wetting and drying cycles.

Chemical and Physical Characteristics

Soil characterization data, including particle size distribution, pH, organic C, carbonates and CEC, are presented in Table 1. Clay contents range from 35.4% in the Ap of the Pyawbwe (Bu-7) to 65.1% in the Bw3 horizon of the same pedon. Weighted average % clay for the particle size family control

section indicates that each one of the three pedons is classed as fine. On a carbonate-free basis, clay contents are such that the Myananda (Bu-4) and Pyawbwe (Bu-7) pedons are classed as very-fine while the Yamethin (Bu-9) remains fine (Fig. 2).

Table 1. Chemical and physical characteristics of selected Vertisols of Burma.

MYANANDA (Bu-4)

Depth cm	Horizon	Coarse Frag.	Sand VC	Sand C	Sand M	Sand F	Sand VF	Sand Total
		%						
0- 13	Ap	0.0	0.6	0.6	0.5	1.7	3.5	6.9
13- 40	Bw1	0.0	0.4	0.2	0.1	1.0	6.1	7.8
40- 63	Bw2	0.0	0.4	0.1	0.1	0.8	2.2	3.6
63- 89	Bw3	0.0	0.6	0.5	0.4	2.1	2.8	6.4
89-118	Bw4	0.0	1.8	1.5	1.1	3.8	5.2	13.4
118-140	Bw5	0.0	2.4	1.8	1.3	4.1	5.1	14.8

Horizon	Silt (μm) 50-20	Silt (μm) 20-5	Silt (μm) 5-2	Silt (μm) Total	Clay (μm) 2–.2	Clay (μm) <.2	Clay (μm) Total	Textural Class	Fi Cl/ Co Cl Ratio
	%								
Ap	9.4	20.5	15.9	45.8	37.6	9.7	47.3	SIC	0.26
Bw1	12.8	19.4	11.5	43.7	33.7	14.8	48.5	SIC	0.44
Bw2	6.8	18.8	13.3	38.9	39.2	18.3	57.5	C	0.47
Bw3	6.5	14.4	11.7	32.6	40.9	20.1	61.0	C	0.49
Bw4	8.3	11.2	8.0	27.5	43.6	15.5	59.1	C	0.36
Bw5	8.5	11.4	7.8	27.7	40.0	17.5	57.5	C	0.44

Horizon	CEC	CEC/ Clay Ratio	(1:1) Water	(0.1M) $CaCl_2$	Org. C	Cal- cite	Dolo- mite	Carbo nate	Cal/ Dol Ratio
	meq/100g		pH		%	Eq.%			
Ap	33.6	0.71	8.0	7.3	0.68	6.4	3.9	10.6	1.64
Bw1	29.0	0.60	8.0	7.5	0.33	5.6	2.4	8.2	2.33
Bw2	34.4	0.60	8.5	7.6	0.39	5.5	3.1	8.8	1.77
Bw3	36.9	0.60	8.6	7.9	0.31	6.0	3.4	9.7	1.76
Bw4	36.1	0.61	8.8	8.1	0.13	5.7	3.1	8.9	1.84
Bw5	36.2	0.63	8.8	8.1	0.21	5.0	3.6	8.8	1.39

Horizon	Fe	Mn
	%	
Ap	0.76	0.056
Bw1	0.80	0.054
Bw2	0.86	0.058
Bw3	0.80	0.074
Bw4	0.44	0.043
Bw5	0.40	0.037

PYAWBWE (Bu-7)

Depth cm	Horizon	Coarse Frag.	Sand VC	Sand C	Sand M	Sand F	Sand VF	Sand Total
		%						
0- 10	Ap	0.0	0.4	0.8	1.9	5.1	5.7	13.9
10- 40	AB	0.0	0.3	0.5	1.4	4.8	4.0	11.0
40- 60	Bw1	0.0	1.4	1.2	3.1	1.0	0.9	7.6
60- 80	Bw2	0.0	0.3	0.6	1.1	4.6	2.9	9.5
80-110	Bw31	0.0	0.4	0.4	0.8	2.9	2.3	6.8
100-125	Bw32	0.0	0.4	0.4	0.9	3.0	1.7	6.4
125-150	Bw33	0.0	0.4	0.3	0.7	2.2	1.1	4.7

Horizon	Silt (μm) 50-20	Silt (μm) 20-5	Silt (μm) 5-2	Silt (μm) Total	Clay (μm) 2–.2	Clay (μm) <.2	Clay (μm) Total	Textural Class	Fi Cl/ Co Cl Ratio
	%								
Ap	18.0	22.6	10.1	50.7	27.4	8.0	35.4	SICL	0.29
AB	10.6	19.5	10.5	40.6	37.9	10.5	48.4	SIC	0.28
Bw1	8.4	18.0	11.4	37.8	40.8	13.8	54.6	C	0.34
Bw2	7.8	17.7	11.3	36.8	39.1	14.6	53.7	C	0.37
Bw31	6.8	16.8	10.3	33.9	43.6	15.7	59.3	C	0.36
Bw32	6.6	13.6	11.8	32.0	46.9	14.7	61.6	C	0.31
Bw33	4.9	12.9	12.4	30.2	48.5	16.6	65.1	C	0.34

Horizon	CEC	CEC/ Clay Ratio	(1:1) Water	(0.1M) $CaCl_2$	Org. C	Cal- cite	Dolo- mite	Carbo nate	Cal/ Dol Ratio
	meq/100g		pH		%	Eq.%			
Ap	28.0	0.79	8.1	7.5	0.38	0.9	2.1	3.3	0.43
AB	37.0	0.76	8.0	7.4	0.31	1.2	1.8	3.2	0.80
Bw1	38.2	0.70	8.0	7.4	0.24	1.1	2.0	3.4	0.55
Bw2	36.9	0.69	8.0	7.4	0.34	0.5	2.1	2.7	0.24
Bw31	41.5	0.70	8.0	7.4	0.23	1.0	1.7	2.9	0.59
Bw32	39.8	0.65	7.9	7.2	0.28	1.3	2.1	3.5	0.62
Bw33	45.8	0.70	7.9	7.2	0.47	0.9	1.3	2.3	0.69

Horizon	Fe	Mn
	%	
Ap	1.3	0.050
AB	1.6	0.058
Bw1	1.8	0.074
Bw2	1.8	0.067
Bw31	1.9	0.064
Bw32	1.6	0.074
Bw33	1.6	0.082

Table 1. CONTINUED

YAMETHIN (Bu-9)

Depth cm	Horizon	Coarse Frag.	Sand VC	Sand C	Sand M	Sand F	Sand VF	Sand Total
		%						
0- 15	Ap	0.0	0.2	0.4	1.2	3.7	3.4	8.9
15- 28	BA	0.0	0.2	0.3	0.8	3.1	2.8	7.2
28- 65	Bw1	0.0	0.0	0.1	0.3	1.6	1.8	3.8
65- 78	Bw2	0.0	0.0	0.1	0.1	0.9	1.3	2.4
78-111	Bw3	0.0	0.0	0.2	0.4	1.3	1.8	3.7
111-149	Bw4	0.0	0.1	0.3	0.4	0.9	1.5	3.2
149-165	Bw5	0.0	0.2	0.4	0.7	1.2	1.4	3.9

Horizon	Silt (μm) 50-20	20-5	5-2	Total	Clay (μm) 2–.2	<.2	Total	Textural Class	Fi Cl/ Co Cl Ratio
	%								
Ap	11.6	24.3	14.0	49.9	30.4	10.8	41.2	SIC	0.36
BA	10.2	23.6	10.6	44.4	33.2	15.2	48.4	SIC	0.46
Bw1	9.7	28.9	12.4	51.0	30.0	15.2	45.2	SIC	0.51
Bw2	8.7	32.5	12.6	53.8	27.4	16.4	43.8	SIC	0.60
Bw3	10.3	28.0	14.4	52.7	29.8	13.8	43.6	SIC	0.46
Bw4	11.6	25.3	12.8	49.7	31.3	15.8	47.1	SIC	0.50
Bw5	8.7	21.9	12.4	43.0	35.1	18.0	53.1	SIC	0.51

Horizon	CEC	CEC/ Clay Ratio	(1:1) Water	(0.1M) $CaCl_2$	Org. C	Cal- cite	Dolo- mite	Carbo nate	Cal/ Dol Ratio
	meq/100g		pH		%	Eq.%			
Ap	33.6	0.82	7.3	7.0	0.63	1.3	2.0	3.4	0.65
BA	35.6	0.74	7.6	7.0	0.61	0.6	1.2	1.9	0.50
Bw1	36.0	0.80	7.6	7.0	0.57	0.5	1.3	1.9	0.38
Bw2	37.0	0.84	7.6	7.0	0.52	0.5	1.3	2.0	0.38
Bw3	39.3	0.90	7.8	7.0	0.69	0.4	1.4	1.9	0.29
Bw4	37.0	0.79	7.8	7.0	0.39	0.4	1.3	1.8	0.31
Bw5	38.9	0.73	7.9	7.1	0.41	0.8	0.6	1.5	1.33

Horizon	Fe	Mn
	%	
Ap	1.3	0.058
BA	1.3	0.058
Bw1	1.3	0.066
Bw2	1.3	0.074
Bw3	1.3	0.072
Bw4	1.5	0.068
Bw5	1.5	0.066

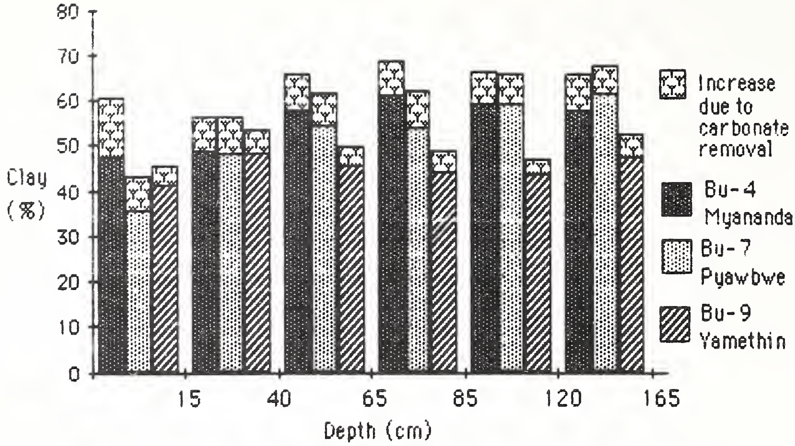

Fig. 2. Carbonate and noncarbonate-free clay distributions for selected Burma Vertisols

Fine clay/coarse clay distributions seem to indicate some clay translocation; however, there was no field evidence of argillans. Silt/sand and fine silt/coarse silt ratios indicate that the original depositional environment for all three soils was non-uniform. All three pedons were free of coarse fragments.

Soil reaction ranges from neutral (pH 7.3) in the surface of the Pyawbwe Vertisol to stongly alkaline (pH 8.8) at 1m in depth for the pedon at Myananda. Reaction values were depressed from 0.3 to 1.2 pH units when measured in dilute $CaCl_2$ solution. These pH values reflect the slow permeability and landscape position of these soils along with the lack of sufficient rainfall to leach them of basic cations.

Organic carbon (OC) values are uniformly low ranging from 0.68% in the surface of the Myananda pedon to 0.13% in the Bw4 horizon of the same soil. The variability of OC levels with depth reflects parent material stratification and the mixing that takes place due to shrink/swell processes. Organic matter contents of Vertisols are nearly always considerably lower than soil colors would otherwise indicate; however, those of the central Burma Vertisols are well below one percent. Low OC levels reflect a "tropustic" environment characterized by long, hot dry seasons unbroken by any sort of significant rainfall and short, drought-prone rainy seasons. Such climatic conditions discourage significant biomass production due to soil moisture limitations and encourage the rapid, year-around oxidation of vegetative material which manages to accumulate on and in the soil surface.

The Myananda pedon (Bu-4) had free carbonate levels which were 2-3× that of the other two soils. It also had a higher proportion of calcite to dolomite. This pedon contained much higher concentrations of snail shells. In all cases carbonates were finely divided and occurred within the matrix of the soil. There was no evidence of concretions or zones of carbonate accumulation in the field. The generally uniform distribution of carbonates with depth (Table 1) supports the field observations and indicates that (1) the leaching environment is severely restricted and (2) argillipedoturbation has provided even mixing throughout the profile.

Cation exchange capacity values along with CEC/clay ratios are indicative of colloidal systems dominated by smectitic minerals which is confirmed by data and discussion in the following section. The CEC/clay ratios are relatively constant with depth and usually are slightly higher in the surface due to the contribution of organic matter.

Free iron oxide levels are considerably lower in the Myananda pedon compared to the Pyawbwe and Yamethin soils. This probably reflects a much longer and more continuous reducing environment for the Myananda pedon as discussed previously. Reductant-soluble Mn levels are relatively constant among all three pedons.

Clay Mineralogy

Semiquantitative estimates of clay mineral composition based on X-ray line intensities and total K_2O contents (Table 2) confirm that the clay mineralogy of all three Vertisols is dominated by smectite. In each case, the general order of clay mineral abundance is smectite (>45%), illite (15-45%), chlorite ≈ kaolinite (5-15%), and quartz (<5%). The clay mineral distributions in pedons Bu-7 and 9 are virtually identical and remain constant to 150 cm depth.

Table 2. Estimated clay (<2μm) mineralogy for selected Vertisols of Burma*

Horizon	Depth -cm-	Illite	Smectite	Chlorite	Kaolinite	Quartz	K_2O %
			Myananda (Bu-4)				
Ap	0- 13	xxxx	xxxxx	x	xx	x	3.3
Bw1	13- 40	xxxx	xxxxx	xx	xx	x	3.2
Bw2	40- 63	xxxx	xxxxx	xx	xx	x	3.2
Bw3	63- 89	xxxx	xxxxx	xx	xx	x	3.1
Bw4	89-118	xxx	xxxxx	xx	xx	x	2.8
Bw5	118-140+	xxx	xxxxx	xx	xx	x	2.8
			Pyawbwe (Bu-7)**				
Ap	0- 10	xxx	xxxxx	xx	xx	x	2.0
AB	10- 40	xxx	xxxxx	xx	xx	x	1.9
Bw1	40- 60	xxx	xxxxx	xx	xx	x	1.9
Bw2	60- 80	xxx	xxxxx	xx	xx	x	1.9
Bw31	80-100	xxx	xxxxx	xx	xx	x	1.9
Bw32	100-125	xxx	xxxxx	xx	xx	x	1.9
Bw33	125-150	xxx	xxxxx	xx	xx	x	1.8
			Yamethin (Bu-9)**				
Ap	0- 15	xxx	xxxxx	xx	xx	x	2.1
BA	15- 28	xxx	xxxxx	xx	xx	x	2.0
Bw1	28- 65	xxx	xxxxx	xx	xx	x	2.0
Bw2	65- 78	xxx	xxxxx	xx	xx	x	1.9
Bw3	78-111	xxx	xxxxx	xx	xx	x	1.9
Bw4	111-149	xxx	xxxxx	xx	xx	x	1.9
Bw5	149-165	xxx	xxxxx	x	xx	x	1.8

*Relative quantities : x = < 5 %; xx = 5-15%; xxx = 15-30%; xxxx = 30-45%; xxxxx = > 45 %

**Contained < 5% goethite througout the pedon.

By comparison, pedon Bu-4 displays higher illite contents in the surface and upper subsoil horizons. Decreases in illite with depth in this profile are reflected in diminished K_2O contents (Table 2) and reduced 1.0 nm peak intensities (Fig. 3). The general absence of clay mineral zonation in any of these soils supports intense self-mixing and/or a mild weathering regime in the central Burma "Dry Zone". The persistence of chlorite in the soil sola is also indicative of base-rich soil environments.

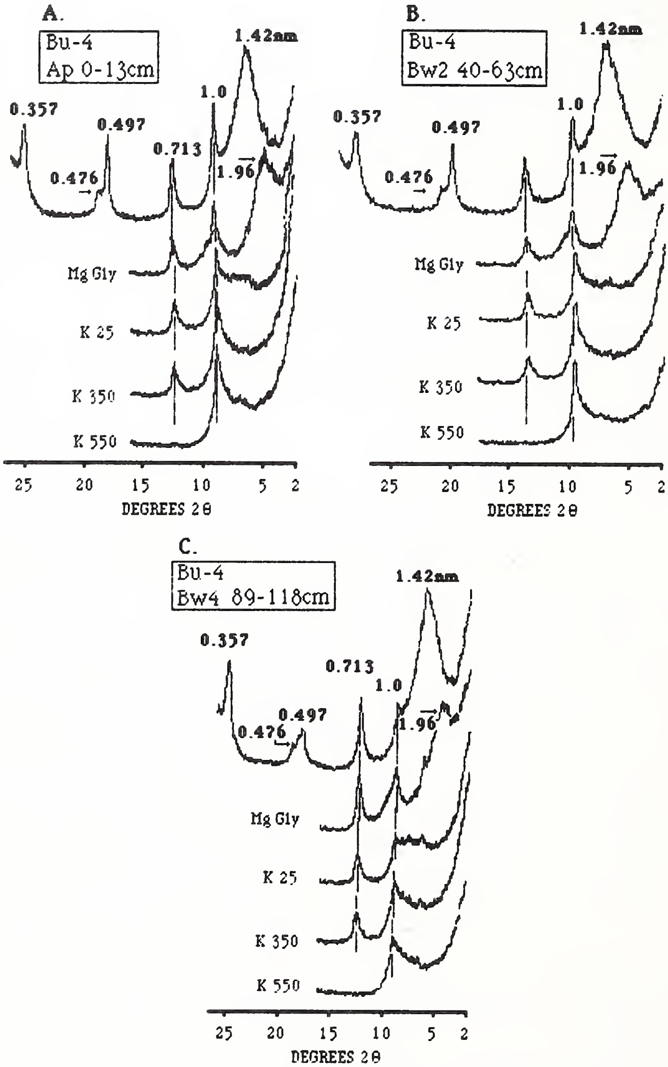

Fig. 3. Representative X-ray diffraction patterns of clay fractions (<2 μm) from the (A) Ap, 0-13 cm; (B) Bw2, 40-63 cm; and (C) Bw4, 89-118 cm, horizons of pedon Bu-4. Mg-25 and Mg-Gly patterns taken from specimens that were Mg-saturated and water or glycerol solvated, respectively, before analysis. K-25, K-350, and K-550 patterns taken from specimens that were K-saturated and air-dried, heated to 350°C, or heated to 550°C, respectively before analysis.

Classification

The classification of the three pedons is listed in Table 3. The higher level of extractable Fe (Table1) in the Pyawbwe and Yamethin pedons is, most likely, the prime reason for their coloration and classification as Chromusterts in contrast to the Myananda which is classified as a Pellustert . The Pyawbwe and Yamethin pedons are classified in the Entic subgroup due to color values (moist) of 4 in the upper 30 cm of their sola. According to Van Wambeke (1985) the boundary between hyperthermic and isohyperthermic soil temperature regimes is located just a few miles south of Mandalay (Fig. 1).

Table 3. Classification of selected Vertisols of Burma according to the U.S. Soil Taxonomy.

Pedon	Classification
Myananda (Bu-4)	Fine, montmorillonitic, hyperthermic, Typic Pellusterts (Ustic Eutraquerts)*
Pyawbwe (Bu-7)	Fine, montmorillonitic, isohyperthermic, Entic Chromusterts (Chromic Eutrusterts)*
Yamethin (Bu-9)	Fine, montmorillonitic, isohyperthermic, Entic Chromusterts (Chromic Eutrusterts)*

*Proposed ICOMERT classification (Comerma et al., 1988).

The ICOMERT proposal (Comerma et al., 1988) affects the suborder, great group, and subgroup placement of the Myanada pedon (Table 3). The Pyawbwe and Yamethin soils remain in the Usterts but classify into a different great group and subgroup. Bu-4 is classified as an Aquert due to low chroma (1 or less) colors on ped faces and in the matrix. This soil is artificially drained during the monsoon for research on cotton and oilseed crops. Soils surrounding the station are used for paddy during the monsoon. All of the pedons are in the “eutric” class at the great group level since pH in 0.01M $CaCl_2$ ranges from 7 to 8.1 for each soil. Both the Pyawbwe and Yamethin soils have matrix and ped face chromas of 2 or higher to a depth of 1m or more, fitting the criteria for placement in the “chromic” subgroup.

Soil Management Considerations

A convenient framework for discussion of soil management parameters is the Fertility Capability Classification (FCC) system developed by Sanchez, et al., (1982). This is a technical system for grouping soils according to the kinds of problems they present for agronomic management. The FCC placement for the three Vertisols of Burma are shown in Table 4.

Each of the soils has both clayey (**C**) topsoil and subsoil which are calcareous (**b**) and are dominated by smectitic clays (**v**). Each also exhibits long periods of time when the subsoil is at the permanent wilting point for plants (**d**=ustic soil moisture regime). The Myananda pedon would be saturated at or near the soil surface for two months or more each year (**g**) were it not artificially drained (Table 4).

Table 4. Fertility Capability Classification (FCC) of selected Vertisols of Burma.

Pedon	Classification*
Myananda (Bu-4)	**Cgdbv***
Pyawbwe (Bu-7)	**Cdbv**
Yamethin (Bu-9)	**Cdbv**

*C = clayey topsoil and subsoil; >35% clay

g = (gley) = soil has <2 chroma colors within 60cm of the surface; soil saturated with water >60 days in most years

d = (dry) = ustic soil moisture regime; subsoil dry >90 cumulative days per year within 20-60cm depth

b = (basic reaction) = free $CaC0_3$ within 50cm of the soil surface (effervescence with HCl); pH >7.3

v = (vertisol) = very sticky plastic clay; >35% clay and >50% of 2:1 expanding clays; severe topsoil shrinking and swelling

The **Cv** combination is indicative of low infiltration rates especially when these soils are saturated during the monsoon. Temporary ponding will occur following intense rainfall. They will become very sticky and very plastic when wet thereby increasing energy investment for primary tillage, planting, intercultivation and mechanical harvesting. **Cv** soils have high water retention capacities but do not have particularly high available water-holding capacities (AWC) especially when compared with loamy soils having relatively high contents of silt. Early primary tillage prior to the monsoon is not facilitated in these particular **Cv** soils because they become very hard when dry. Many **Cv** soils have strong granular structures due to "self-mulching;" however, except for the Yamethin soil, these particular pedons displayed only weak expression of this property. The "vertic" property (**v**) is indicative of management problems such as uneven moistening of the soil with the onset of the rainy season and root-shearing during rainy season droughts. **Cv** soils are strongly buffered against chemical change due to a combination of high surface area and permanent negative charge.

Iron and zinc deficiencies are common in soils which carry the **b** (calcareous) modifier. Urea fertilizer must be carefully managed on these soils. Urea will quickly volatilize to ammonia gas on calcareous soils if it is not incorporated or solubilized. Ammonium sulfate is most likely a better source of N due to its acidifying property and sulfur content. Unfortunately this source of N is no longer either produced or imported in Burma. All N is applied as urea which is produced within the country. Phosphorus fixation by **Cvb** soils is not as severe a problem as for sesquioxide-rich, acid, **Cai** soils; however, P deficiencies are not uncommon on calcareous Vertisols.

The **d** (dry) modifier for each of the soils denotes a prolonged dry season typical of the semiarid tropics. The Usterts of central Burma are preferred over the Ustalfs and other more coarse-textured upland soils for paddy production during the monsoon. Sunflower or chickpea are commonly grown as a post-monsoon crop on residual moisture. If a monsoon crop other than rice is to be grown on these soils then timing of the planting operation is very important. Seedbed preparation and planting must be completed as soon as possible after the rains commence in order to capture the flush of nitrate nitrogen before subsequent precipitation leaches this N out of the rooting zone.

The Myananda soil is very poorly drained as indicated by the g modifier. This particular modifier defines the aquic soil moisture regime which is optimal for paddy production but is unsuitable for most other food crops that are not adapted to anaerobic conditions.

SUMMARY

Three Vertisol pedons from the central Burma "Dry Zone" were investigated in order to provide detailed information on their morphology; chemical, physical and mineralogical characteristics; classification and genesis. Gilgai were absent and slickenside expression was not strong in any of the soils studied. Clay content ranged from 35 to 65% and with removal of carbonates was increased by 3-12%. There was no field evidence of clay illuviation. Soil reaction ranged from neutral (pH 7.3) to strongly alkaline (pH 8.8). The highest organic C level was 0.68% with most horizons containing considerably less. Free carbonates were present in all samples and ranged up to 10.6%; however, there was no evidence of calcic horizon formation. Smectite was the dominant clay mineral (>45 %) followed by illite (15-45 %), chlorite (5-15%) and kaolinite (5-15%). Quartz and goethite occurred in much smaller quantities. The present clay mineral suites were probably inherited from the parent sediments with only minor shifts due to pedogenic weathering. Each of the pedons was fine, montmorillonitic. The northernmost pedon was classified as a hyperthermic Typic Pellustert. The two more southerly soils were isohyperthermic Entic Chromusterts. Free iron oxides ranged from 1.3-1.9% for the Chromusterts to only 0.4-0.9% for the Pellustert. The properties and management of these central Burma Vertisols reflect the impact of climate (tropical wet/dry), landscape position (footslopes or lacustrine plain; seasonally flooded), parent material (clayey, smectite-dominated fluvio-lacustrine sediments) and cultural use (long-term paddy production).

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APPENDIX

Pedon descriptions

Myananda Silty Clay (Bu-4)

Date described:	8/29/86
Location:	Mandalay Division, Patheingyi Township; Myananda Agricultural Research Station, three miles (4.8km) N of Mandalay Hill, 150 feet (46m) SE of the station office.
Vegetation:	Former peanut research trial; soybeans were growing at the edge of the southern face of the pedon where description and sampling took place.
Climate:	Wet/dry subtropics (SMR-Typic tempustic)
Parent Material:	Calcareous lacustrine clays and silts; surrounding mountains are limestone.
Land form:	Valley lake plain
Relief:	Flat
Drainage:	Poorly drained
Salt/Alkali:	Slight
Elevation:	258 feet (78m)
Ground water:	none at 140 cm depth

Horizon	*Depth (cm)*	*Description*
Ap	0-13	Very dark gray(10YR 3/1) when moist; dark gray(10YR 4/1) when dry; silty clay; moderate medium to coarse granular; hard; firm; very sticky; many fine and medium roots; common snail shells; clear smooth boundary; pH 8.0
Bw1	13-40	Very dark gray(10YR3/1) when moist; dark gray(10YR 4/1) when dry; silty clay; strong coarse and very coarse angular blocky; extremely hard; extremely firm; very sticky; very plastic; common pressure faces; common fine and medium roots mainly along ped faces; common snail shells; gradual wavy boundary; pH 8.0
Bw2	40-63	Dark gray(10YR 4/1) silty clay; weak medium and coarse angular, blocky; extremely firm; very sticky; very plastic; common (15-20%) intersecting slickensides inclined at 20-40° from the horizontal; common fine roots along slickenside and ped faces; common snail shells; gradual wavy boundary; pH 8.0
Bw3	63-89	Dark gray(10YR 4/1) silty clay with common fine faint (10YR 4/2) dark grayish brown mottles; weak medium and coarse angular blocky; extremely firm; very sticky; very plastic; common pressure faces; few fine roots; common snail shells; gradual wavy boundary; pH 8.0
Bw4	89-118	Dark gray (5Y 4/1) silty clay; moderate medium and coarse angular blocky; extremely firm; very sticky; very plastic; common, (15-20%) intersecting slickensides inclined at 15-30° from the horizontal; few fine roots primarily along slickenside and ped faces; common snail shells; gradual wavy boundary; pH 8.0
Bw5	118-140+	Dark gray (5Y 4/1) silty clay; moderate medium and coarse angular blocky; extremely firm; very sticky; very plastic; common to many (20-25%) intersecting slickensides inclined at 15-30° from the horizontal; few fine roots primarily along slickenside and ped faces; common snail shells; pH 8.0
Additional notes:		Pedon described and sampled by F. G. Calhoun and U Tin Win with assistance from Ko Myint Zaw and Arlo Thompson. Air temperature approximately 85°F (29°C) under mostly sunny skies. Colors were taken between 10:30-11:00 am and are for moist soil unless otherwise noted . Soil colors were determined using the 2nd edition of Standard Color Charts (Japan). Soil reaction was determined with a Hellige-Truog colorimetric kit.

Pyawbwe Silty Clay Loam (Bu-7)

Date described:	9/3/86
Location:	Mandalay Division, Pyawbwe Township, Chaungmagyi Foundation Seed Farm, Field N1, 21° 30′ N Latitude.
Vegetation:	Natural grasses and thorny acacia.
Climate:	Wet/dry tropics (SMR - Aridic tropustic)
Parent Material:	Fluvio-lacustrine clays
Land form:	Flood plain
Relief:	Flat
Drainage:	Somewhat poorly drained
Salt/Alkali:	none
Elevation:	618 feet (188m)
Ground water:	none at 150 cm depth

Horizon	*Depth (cm)*	*Description*
Ap	0-10	Dark grayish brown (2.5Y 4/2) silty clay loam; moderate medium granular; very firm; very sticky; very plastic; many fine roots; clear smooth boundary; pH 8.0
AB	10-40	Dark grayish brown (2.5Y 4/2) silty clay; weak medium angular blocky; firm; very sticky; very plastic; common pressure faces; few non-intersecting slickensides; common fine roots; gradual smooth boundary; pH 8.0
Bw1	40-60	Very dark grayish brown (2.5Y 3/2) clay; weak medium and coarse angular, wedge-shaped blocky; very firm; very sticky; very plastic; few fine light yellow (2.5Y 7/3) vertical streaks; common (10-15%) intersecting slickensides; common fine roots; gradual wavy boundary; pH 8.0
Bw2	60-80	Very dark grayish brown (2.5Y 3/2) clay; weak medium and coarse angular blocky; extremely firm; very sticky; very plastic; common fine and medium vertical streaks of light yellow (2.5Y7/3) silty clay; many (25-30%) intersecting slickensides inclined 20-40° from the horizontal; few fine roots; gradual wavy boundary; pH 8.0
Bw3	80-150+	Very dark grayish brown (2.5Y 3/2) clay; weak coarse angular blocky; extremely firm; very sticky; very plastic; few fine light yellow (2.5Y 7/3) vertical streaks; many (30-35%) intersecting slickensides inclined 15-30° from the horizontal; few fine roots; pH 8.0; note: this horizon was split into three sampling units as follows: Bw31: 80-150cm Bw32: 100-125cm Bw33: 125-150cm

Additional Notes:

Pedon described and sampled by F.G. Calhoun and U Tin Win with the assistance of U Hla Moe and U Ko Lay. Pedon described during mid and late afternoon under partly cloudy skies. Soil colors were determined using the 2nd edition of Standard Color Charts (Japan). Soil reaction was determined with a Hellige-Truog colorimetric kit.

Pedon was selected as representative of the clayey soils on the farm which were formerly under paddy. This field had not been leveled and old bunds for paddy were still observable. This soil was classified and mapped as Brown Compact (USSR) or Chromic Vertisol by the Land Use Division of the Burma Agriculture Corporation.

Yamethin Silty Clay (Bu-9)

Date described:	9/5/86
Location:	Mandalay Division, Yamethin Township, Sebin Foundation Seed Farm, Field SW7, 21° 20′ N Latitude.
Vegetation:	Sunflower
Climate:	Wet/dry tropics (SMR-Aridic tropustic)
Parent Material:	Fluvio-lacustrine clays
Land form:	Flood plain
Relief:	Flat
Drainage:	Somewhat poorly drained
Salt/Alkali:	None

Elevation:	689 feet (210 m)
Ground water:	None at 165 cm depth

Horizon	*Depth (cm)*	*Description*
Ap	0-15	Dark grayish brown (2.5Y 4/2) silty clay; strong coarse granular; friable; sticky; plastic; many fine and medium roots; clear smooth boundary; pH 8.0
BA	15-28	Dark grayish brown (2.5Y 4/2) silty clay; strong fine and medium angular blocky; firm; sticky; plastic; common, frequently intersecting pressure faces; common fine roots; gradual smooth boundary; pH 8.0
Bw1	28-65	Dark grayish brown (2.5Y 4/2) silty clay; weak medium to coarse angular blocky; firm; sticky; plastic; few coarse grayish brown to dark grayish brown (2.5Y 4.5/3) clay loam pockets; common(10-15%) intersecting slickensides; few fine roots; gradual smooth boundary; pH 8.0
Bw2	65-78	Grayish brown (2.5Y 5/2) silty clay; weak coarse subangular blocky; firm; sticky; plastic; common (5-10%) distinct fine and medium vertical streaks of very dark gray (10YR 3/1); common to many (15-25%) intersecting slickensides; few fine roots; gradual wavy boundary; pH 8.0
Bw3	78-111	Very dark grayish brown to olive gray (3.5Y 4/2) silty clay; weak coarse to very coarse angular blocky; firm; plastic; many (40-50%) medium and coarse distinct vertical streaks of very dark gray (10YR 3/1); many (25-35%) intersecting slickensides inclined 20-45° from the horizontal; gradual wavy boundary; pH 8.0
Bw4	111-149	Dark grayish brown (2.5Y 4/3,crushed) silty clay; weak coarse to very coarse angular blocky; firm; plastic; common intersecting slickensides inclined 15-35° from the horizontal; slickenside faces are dark grayish brown (2.5Y 4/2); common fine faint light olive brown mottles(2.5Y 5/4); few fine roots; gradual wavy boundary; pH 8.0
Bw5	149-165+	Dark grayish brown (2.5Y 4/3,crushed) silty clay; very weak coarse angular blocky; firm; plastic; sticky; common intersecting slickensides inclined 15-35° from the horizontal; common fine faint light olive brown (2.5Y 5/4) mottles; few fine roots; gradual wavy boundary; pH 8.0

Additional notes:

Pedon described and sampled by F.G. Calhoun and U Tin Win. Pedon described during the morning under partly cloudy skies. Soil colors were determined using the 2nd edition of Standard Color Charts (Japan). Colors are for moist soil and were read between 9:30 and 10:15am. Soil reaction was determined with a Hellige-Truog colorimetric kit.

Pedon was selected as representative of the clayey soils on the farm which were formerly under paddy. This soil was classified and mapped as Brown Compact (USSR) or Chromic Vertisol (FAO) by the Land Use Division of the Burma Agriculture Corporation.

Chapter 3

CONCEPTUAL CHANGES IN THE CLASSIFICATION OF VERTISOLS

J. A. Comerma, D. Williams and A. Newman

INTRODUCTION

To a large extent, Soil Classification Systems reflect our current state of knowledge. Historically, Vertisols have been considered as a group of soils that reflect slow internal drainage, are high in base status, have smectite-dominated mineralogy, and a strong churning process that imparts important morphological marks. Examination of Vertisols in new areas and the review of past data have pointed out a variety of situations that need attention in a revised class of Vertisols. This revision is based on properties that reflect different genetic processes associated with high shrinking and swelling as well as important characteristics and qualities that strongly affect the use and management of these soils. Hydromorphism, acidification and sodification are among the most important of these genetic processes.

Some important issues have surfaced in the past 10 to 15 years as Soil Taxonomy was applied to Vertisols. The concept that "pell" and "chrom" would effectively separate drainage condition has not worked out satisfactorily. Pell was to indicate the poorly drained Vertisols and chrom the better drained ones. A later proposal to add slope did not improve the situation. This proposal would have required chrom to have slopes of more than 1 percent and pell to have slopes of less than 1 percent. Unfortunately, many of the chrom Vertisols have less than 1 percent slope and have poor or very poor drainage conditions.

The lack of a provision for reaction classes caused concern in several locations. In applying Taxonomy, several profiles were found to be extremely acid and containing high quantities of aluminum. Acidity is considered to be an important issue because it is directly related to aluminum toxicity and availability of nutrients to plants.

Many scientists have pointed out the need to recognize Vertisols high in sodium and salts. A provision was made for sodium at the subgroup level in the 7th Approximation, but later on it was dropped. The reason for its elimination is not documented. Sodium has important agronomic interpretations as would the presence of a salic horizon. Salinity levels lower than those required for a salic horizon could likely be handled a phase criteria.

Another issue is the lack of a clear cut provision to separate Vertisols from vertic intergrades. Many soils meet the clay content, depth, and cracking criteria requirement of Vertisols, but do not fulfill the other basic requirements. This proposal will attempt to establish the criteria for separation.

The International Committee on Classification of Vertisols (ICOMERT) with Dr. J. A. Comerma as chairman accepted the responsibility of pulling together the ideas and experiences of those familiar with Vertisols. After four circular letters, ICOMERT has proposed several changes to the classification of Vertisols including a Key To The Order of Vertisols. The more important proposed changes, at different categorical levels, are presented in this paper.

ORDER

The main change at the Order level is in the de-emphasis of churning as the main process that originates the necessary morphological features for Vertisols. The elimination of gilgai reflects this de-emphasis. It is proposed that gilgai will no longer be an alternative at the order level sufficient to classify a soil as a Vertisol. Not all Vertisols have gilgai and other surface phenomena can be confused with gilgai such as piping, deflation, biological mounds and patterned ground. Cultivation and leveling eliminate, at least temporarily, the evidence of surface gilgai. However, wedge shaped aggregates and slickensides remain as alternative criteria. The implication is that other physical processes associated with swelling and shrinking, but different from churning, can produce intersecting slickensides or tilted parallelepipeds (Blockhuis, 1982; Hubble, 1984) without the microrelief of gilgai. At the highest categorical level emphasis should be placed on genetic properties within the soil. Slickensides is the common thread to all Vertisols.

A second modification is related to the need to establish a limit between Vertisols and other soils that meet the clay content, depth and cracking criteria of Vertisols but do not behave as Vertisols. In the latter soils, the effect of swelling and shrinking, as expressed by intersecting slickensides or tilted parallelepipeds, is not sufficiently well expressed to imply significant physical activity. This may imply limited physical activity due to kind of clay, moisture regimes too dry, moisture regimes too moist, insufficient swelling and shrinking cycles, or a combination of the above. A minimum limit of 10 percent of slickenside features in the solum is proposed. Testing of this proposal to date indicate that slickensides between 25 and 100 centimeters in well expressed Vertisols constitute about 20 to 40 percent of the natural structural surfaces. The percent of slickensides faces is determined after picking a pit wall to expose natural structural surfaces and estimating the percent slickenside faces exposed to the total area examined. A weighted average of the 25 to 100 centimeters depth is used.

The establishment of a minimum weighted average of 10 percent of slickensides between 25 and 100 centimeters would eliminate from Vertisols those soils with just a few slickensides. Many of these would be included with vertic intergrades.

SUBORDER

At the suborder level, a class for Vertisols dominated by present hydromorphic conditions, and another for those occurring in cold regions have been proposed. For the first class a different way, from the present, of defining an aquic moisture regime has been suggested (Comerma, 1985). This procedure is based on water saturation inferred from tensiometers or piezometers, and/or water saturation and reduction inferred from dyes that indicate presence of Fe^{++}. This would represent an alternate way, from the auger hole method, of characterizing the condition of water saturation as a prerequisite for soils that have an aquic moisture regime. Color criteria alone, used in most other suborders in Taxonomy, do not work for Vertisols. Many Vertisols are derived from dark colored parent materials and/or have been reduced during deposition giving an inherited low chroma color. Although the "pell" and "chrom" did not make the desired separations according to drainage conditions, the separation is being maintained at the subgroup level for other purposes. Color is a reflection of parent material which influences many physical and chemical properties of the soil.

Vertisols occurring in cold regions, with frigid or cryic soil temperature regimes, were originally excluded in Soil Taxonomy for unknown reasons. These have recently been incorporated into Soil Taxonomy. Consequently, a suborder of Borerts equivalent to the other orders is proposed.

GREAT GROUP

At the Great Group level, two important conceptual changes are under discussion. These changes represent modifications of our present model of Vertisols and that of hydromorphic soils in other orders of Soil Taxonomy. In various Suborders it was considered important, genetically as well as from the point of view of land use, to separate acid from non-acid Vertisols (Ahmad, 1985; Comerma, 1985). Acid Vertisols represent an important departure from the classical concept of these soils, but they occur and are significantly different from other soils of the same class (Ahmad, 1985). The significance and limits for these two classes are still under discussion. A limit of soil pH of 4 or 4.5, using KCI or $CaCl_2$, in the upper solum to reflect a critical Al saturation level for plants seems promising. In the case of the hydromorphic Vertisols (Aquerts), there is the proposal to separate those in which water saturation comes partially or totally from the soil surface (Epiaquerts), showing water ponding, and those in which water saturation is from groundwater sources. The last item of significance is the subdivision of arid Vertisols (Torrerts) with similar criteria as in Aridisols; that is, a class of soils with a salic horizon and a water table, and those without it.

SUBGROUPS

At the subgroup level, several subgroups are proposed that have similar definitions as used in other orders. Subgroups with new names or new meanings are also being proposed. New subgroups include Leptic, Chromic-Pellic and Sodic. Leptic include soils that have Vertisol features, clay content and presence of slickensides or wedge shaped aggregates at more than 50 centimeters but less than 1 meter in thickness. Both hard and soft contacts are included in the definition of Leptic. Chromic and Pellic have the same definition as present and would imply color reflecting parent material influence and/or degree of mineral-organic associations. In general, the darker Pellic are also better structured and would correspond with the central concept (Typic) of the Great Group.

FAMILIES

At the family level, the use of fine and very fine, and mineralogy families are to be retained. The only proposal is separating calcareous from non-calcareous Vertisols.

PENDING ISSUES

The most important pending issues are: (1) the acceptance of the definition of the aquic moisture regime proposed and that of Aquerts, (2) the definition of what an acid Vertisol should be, (3) definitions and limits of a new suborder of Borerts, and (4) an improved definition of a class of Vertisols grouping the ones that are better structured from the ones which are rather massive especially in the upper layers. Specific studies are needed to establish the relationship between organic matter content, manganese, iron, and temperature in saturated Vertisols. The International Committee on Aquic Moisture Regimes (ICOMAQ) is expected to make recommendations for aquic moisture regimes in all orders. A method other than the unlined auger borehole is needed to measure a saturated condition in Vertisols. One possibility is the use of tensiometers. A second possibility is the use of dyes such as dipirydil to detect the presence of reduced iron.

A pH of 5.0 (water 1:1) seems to be a general breaking point where siqnificant amounts of exchangeable aluminum start to affect use and management. In the presence of salts, pH does not seem to truly indicate aluminum toxicity. Limited data indicates that salinity levels of more than 4 millimhos per centimeter confounds the relationship between pH and aluminum saturation. The use of 1N KCL pH may be the answer, but additional research is needed to determine the critical pH. The last issue of separating better structured Vertisols from ones that are rather massive has important consequences from the genetic as well as from the interpretative point of view. However, it has been dealt with before during early development of taxonomy using Grum and Maz. It was dropped because of unsatisfactory results.

PROPOSED KEY

The following is a proposed key to the Order of Vertisols. It includes the proposals made in this paper at the various categorical levels. Following the proposed key is an appendix listing the present classification and the corresponding classification in the ICOMERT proposal of Vertisols occurring in the southern states of the United States.

Order

D. Other soils that

1. Do not have a lithic or paralithic contact, petrocalcic horizon, or duripan within 50 cm of the surface; and
2. After the soil to a depth of 18 cm has been mixed, as by plowing, have 30% or more clay in all subhorizons to a depth of 50 cm or more; and
3. Have at some time in most years, unless irrigated or cultivated, open cracks[1] at a depth of 50 cm that are at least 1 cm wide and extend upward to the surface or to the base of the plow laver or surface crust; and
4. Between a depth of 25 cm and 1 m or to a lithic or paralithic contact, a petrocalcic horizon, or a duripan, have 10% or more (as a weighted average) of the aggregates or of the major ped surfaces constituted by either:

a. wedge shaped aggregates, or

b. slickensides close enough to intersect

In both cases they should have their long axis tilted 10° to 60° to be accountable.

Vertisols

Suborders

DA. Vertisols that lack a salic horizon whose upper boundary is within 75 cm of the surface, and have an aquic moisture regime or are artificially drained and have within 50 cm of the surface, in more than half of each pedon, dominant color[2] (moist) on ped faces, or in the matrix if peds are absent, as follows:

1. If there is mottling, chroma is 2 or less; or
2. If there is no mottling, chroma is 1 or less.

Aquerts

DB. Other Vertisols that have a cryic but not a pergelic soil temperature regime

Borerts

[1]An open crack is interpreted to be a separation between gross polyhedrons. If the surface horizons are strongly self-mulching, that is, if the soil is a mass of loose granules, or if the soil is cultivated while the cracks are open, the cracks may be largely filled with granular materials from the surface. But they are considered to be open in the sense that the polyhedrons are separated.

[2]If the hue is redder than 10YR because of red parent materials that remain red after citrate-dipthionite extraction, the requirement for low chroma is waived.

DC. Other Vertisols that have a thermic, mesic, or frigid soil temperature regime and, unless irrigated, have cracks that open and close once each year and remain open for 60 consecutive days or more in the 90 days following the summer solstice in more than 7 out of 10 years but that are closed for 60 consecutive days or more during the 90 days following the winter solstice

Xererts

DD. Other Vertisols that, have in most years cracks that either remain open throughout the year or are closed for less than 60 consecutive days at a period when the soil temperature at a depth of 50 cm is continuously higher than 8°C, or are saturated within 1 m of the surface for 1 month or more in some years and have a salic horizon whose upper boundary is within 75 cm of the surface

Torrerts

DE. Other Vertisols that have cracks that open and close one or more times during the year in most years but do not remain open for as many as 90 cumulative days in most years

Uderts

DF. Other Vertisols

Usterts

Great Groups

Aquerts

DAA. Aquerts that having an EC of the saturation extract less than 4 mmhos/cm at 25°C have a pH equal or less than 5.0 in 1:1 water or 4.5 in 0.01 M CaCl2 in the major part of the upper 50 cm in more than half of each pedon

Dystraquerts

DAB. Other Aquerts that have a duripan with its upper boundary within 1 m of the surface.

Duraquerts

DAC. Other Aquerts that are subject to at least a few continuous days of ponding each year in more than 7 out of 10 years.

Epiaquerts

DAD. Other Aquerts.

Eutraquerts

Xererts

DCA. Xererts that have a duripan with its upper boundary within 1 m of the surface.

Durixererts

DCB. Other Xererts.

Haploxererts

Torrerts

DDA. Torrerts that have a salic horizon whose upper boundary is within 75 cm of the surface and are saturated with water within a depth of 1 m for one month or more in some years or are artificially drained.

Salitorrerts

DDB. Other Torrerts.

Haplotorrerts

Uderts

DEA. Uderts that having an EC of the saturation extract less than 4 mmhos/cm at 25°C have a pH of 5 or less in 1:1 water or 4.5 in 0.01 M $CaCl_2$ in the major part of the upper 50 cm in more than half of each pedon

Dystruderts

DEB. Other Uderts

Eutruderts

Usterts

DFA. Usterts that havinq an EC of the saturation extract less than 4 mmhos/cm at 25°C have a pH of 5 or less in 1:1 water or 4.5 in 0.01 M $CaCl_2$ in the major part of the upper 50 cm in more than half of each pedon.

Dystrusterts

DFB. Other Usterts.

Eutrusterts

Subgroups

Dystraquerts

Typic Dystraquerts are the Dystraquerts that

a. Have in 60 percent of more of the matrix in all subhorizons down to a depth of 75 cm one or more of the following:
   (1) If mottled and if hue is 2.5Y or redder and the value, moist, is 5, the chroma, moist, is 2 or less; if the value, moist, is 5 or less, the chroma, moist, is 1 or less;
   (2) If mottled and the hue is yellower than 2.5Y, the chroma, moist, is 2 or less;
   (3) The chroma, moist, is 1 or less whether mottled or not.
b. Do not have within a depth of 1 m from the soil surface, any layer,

horizon or contact, except a duripan, that interrupts the presence of slickensides and/or wedge shaped aggregates.

c. Do not have either of the following:
   (1) Jarosite mottles and a pH between 3.5 and 4.0 (1:1 water, air dried slowly in shade) in some subhorizons within 50 cm of the soil surface; or
   (2) Jarosite mottles and a pH 4 (1:1 water, air dried slowly in shade) in some subhorizon between depths of 50 and 100 cm.

d. Have both of the following:
   (1) Cracks that open and close one or more times during the year in most years, and remain open for 150 or more cumulative days; and
   (2) Closed cracks for 60 consecutive days or more in most years at a time when the soil temperature at a depth of 50 cm is continuously above 8°C.

   Aeric Dystraquerts are like the Typic Dystraquerts except for a.
   Leptic Dystraquerts are like the Typic Dystraquerts except for b.
   Sulfic Dystraquerts are like the Typic Dystraquerts except for c.
   Udic Dystraquerts are like the Typic Dystraquerts except for d1.
   Xeric Dystraquerts are like the Typic Dystraquerts except for d2.

Duriaquerts

Typic Duriaquerts are the Duriaquerts that

a. Have in 60 percent of more of the matrix in all subhorizons down to a depth of 75 cm one or more of the following:
   (1) If mottled and if hue is 2-5Y or redder and the value, moist, is more than 5, the chroma, moist is 2 or less; if the value, moist, is 5 or less, the chroma, moist, is I or less;
   (2) If mottled and the hue is yellower than 2.5Y, the chroma, moist, is 2 or less;
   (3) The chroma, moist, is 1 or less whether mottled or not.

b. Have cracks that open once a year for 60 consecutive days or more in the 90 days following the summer solstice, and have a thermic, mesic or frigid soil temperature regime.

   Aeric Duriaquerts are like the Typic Duriaquerts except for a.
   Ustic Duriaquerts are like the Typic Duriaquerts except for b.

Epiaquerts

Typic Epiaquerts are the Epiaquerts that

a. Have in 60 percent of more of the matrix in all subhorizons down to a depth of 75 cm one or more of the following:
   (1) If mottled and if hue is 2.5Y or redder and the value, moist, is 5, the chroma, moist, is 2 or less; if the value, moist, is 5 or less, the chroma, moist, is 1 or less;,

(2) If mottled and the hue is yellower than 2.5Y, the chroma, moist, is 2 or less;

The chroma, moist, is 1 or less whether mottled or not

b. Do not have within a depth of 1 m from the soil surface, any layer, horizon or contact that interrupts the presence of slickensides and/or wedge shaped aggregates.

c. Do not have within a depth of 1 m any subhorizon with a value of 15 ESP or 13 SAR or more.

d. Have both of the following:

(1) Cracks that open and close one or more times during the year in most years,and remain open for 150 or more cumulative days; and

(2) Have cracks that are closed for 60 consecutive days or more in most years at a time when the soil temperature at a depth of 50 cm is continuously above 8°C

Aeric Epiaquerts are like the Typic Epiaquerts except for a.

Leptic Epiaquerts are like the Typic Epiaquerts except for b.

Sodic Epiaquerts are like the Typic Epiaquerts except for c.

Udic Epiaquerts are like the Typic Epiaquerts except for d1.

Xeric Epiaquerts are like the Typic Epiaquerts except for d2.

Eutraquerts

Typic Eutraquerts are the Eutraquerts that

a. Have in 60 percent of more of the matrix in all subhorizons down to a depth of 75 cm one or more of the following:

(1) If mottled and if hue is 2.5Y or redder and the value, moist, is 5, the chroma, moist, is 2 or less; if the value, moist, is 5 or less, the chroma, moist, is 1 or less;

(2) If mottled and the hue is yellower than 2.5Y, the chroma, moist, is 2 or less;

(3) The chroma, moist, is 1 or less whether mottled or not.

b. Do not have within a depth of 1 m from the soil surface, any layer, horizon or contact, that interrupts the presence of slickensides and/or wedge shaped aggregates.

c. Do not have within a depth of 1 m any subhorizon with a value of 15 ESP or 13 SAR or more.

d. Have both of the following:

(1) cracks that open and close one or more times during the year in most years but do not remain open for as many as 90 cumulative days; and

(2) have cracks that are closed for 60 consecutive days or more in most years at a time when the soil temperature at a depth of 50 cm is continuously above 8°C.

Aeric Eutraquerts are like the Typic Eutraquerts except for a.

Leptic Eutraquerts are like the Typic Eutraquerts except for b.

Sodic Eutraquarts are like the Typic Futraquerts except for c.

Ustic Eutraquerts are like the Typic Eutraquerts except for d1.
Xeric Eutraquerts are like the Typic Eutraquerts except for d2.

Durixererts

The Typic Durixererts are the Durixererts that

a. Have chroma, moist, of 1 or less throughout the upper 30 cm in more than half of each pedon.

b. Have a platy or massive duripan that is indurated in some subhorizon.

c. Have cracks that open once a year for 90 to 180 consecutive days.

Aridic Durixererts are like the Typic Durixererts except for c and the cracks are open once a year for more than 180 consecutive days.

Chromic Durixererts are like the Typic Durixererts except for a.

Haplic Durixererts are like the Typic Durixererts except for b.

Udic Durixererts are like the Typic Durixererts except for c and the cracks are open once a year for less than 90 consecutive days.

Haploxererts

The Typic Haploxererts are the Haploxererts that

a. Have chroma, moist, of 1 or less throughout the upper 30 cm in more than half of each pedon

b. Do not have within a depth of 1 m from the soil surface, any layer, horizon, or contact, that interrupts the presence of slickensides and/or wedge shaped aggregates.

c. Have cracks that open once a year for 90 to 180 consecutive days.

Aridic Haploxererts are like the Typic Haploxererts except for c and the cracks are open once a year for more than 180 consecutive days.

Chromic Haploxererts are like the Typic Haploxererts except for a.

Leptic Haploxererts are like the Typic Haploxererts except for b.

Udic Haploxererts are like the Typic Haploxererts except for c and the cracks are open once a year for less than 90 consecutive days.

Salitorrert

Haplotorrert

The Typic Haplotorrerts are the Torrerts that

a. Do not have within a depth of 1 m from the soil surface any layer, horizon or contact, that interrupts the presence of slickensides and/or wedge shaped aggregates.

Leptic Haplotorrerts are like the Typic Haplotorrerts except for a.

Dystruderts

The Typic Dystruderts are the Dystruderts that

a. Have chroma, moist, of 1 or less throughout the upper 30 cm in more

than half of each pedon

b. Do not have within a depth of 1 m from the soil surface, any layer, horizon or contact, that interrupts the presence of slickensides and/or wedge shaped aggregates.

Chromic Dystruderts are like the Typic Dystruderts except for a.

Leptic Dystruderts are like the Typic Dystruderts except for b.

Eutruderts

The Typic Eutruderts are the Eutruderts that

a. Have chroma, moist, of 1 or less throughout the upper 30 cm in more than half of each pedon

b. Do not have within a depth of 1 m from the soil surface, any layer, horizon or contact, that interrupts the presence of slickensides and/or wedge shaped aggregates.

Chromic Eutruderts are like the Typic Eutruderts except for a.

Leptic Eutruderts are like the Typic Eutruderts except for b.

Dystrusterts

The Typic Dystrusterts are the Dystrusterts that

a. Have chroma, moist, of 1 or less throughout the upper 30 cm in more than half of each pedon

b. Do not have within a depth of 1 m from the soil surface, any layer, horizon or contact, that interrupts the presence of slickensides and/or wedge shaped aggregates.

c. Have cracks that are open one or more times during the year in most years and remain open for 150 to 210 cumulative days.

Aridic Dystrusterts are like the Typic Dystrusterts except for c and their cracks remain open for more than 210 cumulative days.

Chromic Dystrusterts are like the Typic Dystrusterts except for a.

Leptic Dystrusterts are like the Typic Dystrusterts except for b.

Udic Dystrusterts are like the Typic Dystrusterts except for c and their cracks remain open for less than 150 cumulative days.

Eutrusterts

The Typic Eutrusterts are the Eutrusterts that

a. Have chroma, moist, of 1 or less throughout the upper 30 cm in more than half of each pedon

b. Do not have within a depth of 1 m from the soil surface, any layer, horizon or contact that interrupts the presence of slickensides and/or wedge shaped aggregates.

c. Do not have within a depth of 1 m any subhorizon with a value of 15 ESP or 13 SAR or more.

d. Have cracks that are open one or more times during the year in most

years and remain open for 150 to 210 cumulative days.

Aridic Eutrusterts are like Typic Eutrusterts except for d and their cracks remain open for more than 210 cumulative days.

Chromic Eutrusterts are like Typic Eutrusterts except for a.

Leptic Eutrusterts are like Typic Eutrusterts except for b. Sodic Eutrusterts are like Typic Eutrusterts except for c.

Udic Eutrusterts are like Typic Eutrusterts except for d and their cracks remain open for less than 150 cumulative days.

APPENDIX

CLASSIFICATION OF VERTISOLS IN THE SOUTHERN STATES

Series	Current Classification	Proposed ICOMERT Classification
Catarina	Typic Torrerts	Typic Haplotorrerts (Sodic) [1]
Dalby	Typic Torrerts	Typic Haplotorrerts (Leptic?) [2]
Montoya	Mollic Torrerts	Typic Haplotorrerts (Leptic?) [2]
Verhalen	Mollic Torrerts	Typic Haplotorrerts
Camaquey	Typic Pelluderts	Typic Eutruderts
Francitas	Typic Pelluderts	Sodic (Udic) Epiaquerts [3]
Hollywood	Typic Pelluderts	Typic Eutruderts
Kaman	Typic Pelluderts	Udic Epiaquerts
Kaufman	Typic Pelluderts	Udic Epiaquerts
Lake Charles	Typic Pelluderts	Udic Epiaquerts (Typic Eutruderts) [2]
Texark	Typic Pelluderts	Udic Epiaquerts
Trinity	Typic Pelluderts	Udic Epiaquerts
Wiergate	Typic Pelluderts	Typic Eutraquerts
Bacliff	Entic Pelluderts	Udic Epiaquerts
Beaumont	Entic Pelluderts	Udic Dystraquerts
Eutaw	Entic Pelluderts	Leptic Dystraquerts
Garner	Entic Pelluderts	Typic Eutraquerts
Billyhaw	Typic Chromuderts	Chromic Eutruderts
Brazoria	Typic Chromuderts	Chromic Eutruderts
Houston	Typic Chromuderts	Chromic Eutruderts
Okolona	Typic Chromuderts	Chromic Eutruderts
Bayoudan	Aquentic Chromuderts	Chromic Dystruderts
Bellwood	Aquentic Chromuderts	Aeric Dystraquerts
Burkeville	Aquentic Chromuderts	Typic Eutraquerts
Dylan	Aquentic Chromuderts	Chromic Eutruderts
Faunsdale	Aquentic Chromuderts	Chromic Eutruderts
Lacerda	Aquentic Chromuderts	Aeric (Udic) Dystraquerts [3]
Lebeau	Aquentic Chromuderts	Aeric Eutraquerts (Aeric (Udic) Epiaquerts) [2/3]
Louin	Aquentic Chromuderts	Aeric (Udic) Dystraquerts [3]
Naclina	Aquentic Chromuderts	Chromic Eutruderts
Raylake	Aquentic Chromuderts	Aeric (Udic) Dystraquerts [3]
Redco	Aquentic Chromuderts	Aeric (Ustic) Eutraquerts [3]
Sucarnoochee	Aquentic Chromuderts	Aeric (Udic) Epiaquerts [3]
Vamont	Aquentic Chromuderts	Aeric Eutraquerts

Series	Current Classification	Proposed ICOMERT Classification
Brooksville	Aquic Chromuderts	Typic Eutraquerts
Terouge	Aquic Chromuderts	Aeric Eutraquerts
Zilaboy	Aquic Chromuderts	Aeric (Udic) Epiaquerts [3]
Maytag	Entic Chromuderts	Chromic Eutruderts
Morse	Entic Chromuderts	Chromic Eutruderts
Tahoula	Entic Chromuderts	Chromic Eutruderts
Danjer	Typic Pellusterts	Typic Eutrusterts
Lattas	Typic Pellusterts	Typic Eutrusterts
Monteola	Typic Pellusterts	Typic Futrusterts
Roscoe	Typic Pellusterts	Typic Eutrusterts
Leemont	Entic Pellusterts	Udic Eutrusterts
Lipan	Entic Pellusterts	Udic Epiaquerts
Montell	Entic Pellusterts	Sodic Eutrusterts
Aquirre	Udic Pellusterts	Sodic Eutrusterts
Bleiblerville	Udic Pellusterts	Udic Eutrusterts
Branyon	Udic Pellusterts	Udic Eutrusterts
Buchel	Udic Pellusterts	Udic Eutrusterts
Burleson	Udic Pellusterts	Udic Eutrusterts
Clarita	Udic Pellusterts	Udic Eutrusterts
Dalco	Udic Pellusterts	Leptic (Udic) Eutrusterts [3]
Dimebox	Udic Pellusterts	Udic Eutrusterts
Fairlie	Udic Pellusterts	Udic Eutrusterts
Greenville	Udic Pellusterts	Leptic (Udic) Eutrusterts [3]
Guanica	Udic Pellusterts	Sodic (Ustic) Eutraquerts [3]
Houston Black	Udic Pellusterts	Udic Eutrusterts
Leson	Udic Pellusterts	Udic Eutrusterts
Ness	Udic Pellusterts	Udic Epiaquerts (Leptic?) [2]
Paso Seco	Udic Pellusterts	Leptic (Chromic) (Udic) Eutrusterts [3]
Poncena	Udic Pellusterts	Leptic (Udic) Eutrusterts [3]
Randall	Udic Pellusterts	Udic Epiaquerts
San Saba	Udic Pellusterts	Leptic (Udic) Eutrusterts [3]
Santa Isabel	Udic Pellusterts	Udic Eutrusterts
Slidell	Udic Pellusterts	Udic Eutrusterts
Tiocano	Udic Pellusterts	Udic Epiaquerts
Victine	Udic Pellusterts	Sodic (Udic) Epiaquerts [3]
Victoria	Udic Pellusterts	Udic Eutrusterts
Watonga	Udic Pellusterts	Udic Eutrusterts
Arroyada	Udorthentic Pellusterts	Sodic (Udic) Epiaquerts [3]
Benito	Udorthentic Pellusterts	Sodic (Udic) Epiaquerts [3]
Deport	Udorthentic Pellusterts	Udic Eutrusterts
Frelsburg	Udorthentic Pellusterts	Udic Eutrusterts
Lomalta	Udorthentic Pellusterts	Sodic (Udic) Epiaquerts [3]
Mercedes	Udorthentic Pellusterts	Sodic (Udic) Eutrusterts [3]
Leeray	Typic Chromusterts	Chromic Eutrusterts
Stamford	Typic Chromusterts	Leptic (Chromic) Eutrusterts [3]
Tobosa	Typic Chromusterts	Chromic Eutrusterts
Cochina	Entic Chromusterts	Chromic (Udic) Eutrusterts [3]
Cotulla	Entic Chromusterts	Sodic (Chromic)(Udic) Eutrusterts [3]
Harligen	Entic Chromusterts	Chromic (Udic) Eutrusterts [3]
Lasalle	Entic Chromusterts	Sodic (Chromic) Eutrusterts [3]
Reap	Entic Chromusterts	Chromic Eutrusterts

Series	Current Classification	Proposed ICOMERT Classification
Indiahoma	Paleustollic Chromusterts	Chromic Eutrusterts
Anhalt	Udic Chromusterts	Leptic (Chromic) (Udic) Eutrusterts [3]
Cartagena	Udic Chromusterts	Sodic (Chromic) Eutrusterts [3]
Crawford	Udic Chromusterts	Leptic (Chromic) (Udic) Eutrusterts [3]
Depalt	Udic Chromusterts	Chromic (Udic) Eutrusterts (Leptic?) [3]
3Fe	Udic Chromusterts	Sodic (Chromic) Eutrusterts [3]
Fraternidad	Udic Chromusterts	Chromic (Udic) Eutrusterts [3]
Heiden	Udic Chromusterts	Chromic (Udic) Eutrusterts [3]
Lela	Udic Chromusterts	Udic Eutrusterts
Luling	Udic Chromusterts	Chromic (Udic) Eutrusterts [3]
Ovan	Udic Chromusterts	Chromic (Udic) Eutrusterts [3]
Sanger	Udic Chromusterts	Chromic (Udic) Eutrusterts [3]
Seagoville	Udic Chromusterts	Leptic (Chromic) (Udic) Eutrusterts [3]
Ships	Udic Chromusterts	Chromic (Udic) Eutrusterts [3]
Tamford	Udic Chromusterts	Chromic (Udic) Eutrusterts [3]
Coquat	Udorthentic Chromusterts	Sodic (Chromic) Eutrusterts [3]
Ferris	Udorthentic Chromusterts	Chromic (Udic) Eutrusterts [3]
Latium	Udorthentic Chromusterts	Chromic (Udic) Eutrusterts [3]
Medlin	Udorthentic Chromusterts	Chromic (Udic) Eutrusterts [3]
Vertel	Udorthentic Chromusterts	Leptic (Udic) Eutrusterts [3]

[1]Series is also sodic, but sodic is not currently recognized in Torrerts.
[2]Additional study is needed to determine proper classification.
[3]Series also qualifies for subgroup in parenthesis.

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Chapter 4

GENESIS OF VERTISOLS: SHRINK-SWELL PHENOMENA

L.P. Wilding and D. Tessier

INTRODUCTION

Shrink-swell phenomena in soils are a complex, dynamic but incompletely understood set of processes responsible for the genesis and behavior of Vertisols. Expressions of this phenomena are (1) linear and normal gilgai, (2) cyclic horizonation, (3) surface cracking upon desiccation, and (4) slickenside formation. Of the above properties slickensides are the unifying morphogenetic marker found in all Vertisols.

The purposes of this paper are to: (1) briefly review several pedological models of Vertisols (2) consider factors affecting shrink-swell potential, and (3) illustrate micor- and submicroscopic evidences of shrink-swell activity.

PEDOGENIC MODELS OF VERTISOLS

While turbation and inversion have long been emphasized as dynamic, genetic processes in Vertisols (L. *verto*, turn), recent evidence suggests that many Vertisols do not experience extensive mixing, especially in upper sola (Ahmad, 1983; Wilding, 1985; Dasog et al., 1987). For example, the rate of churning is not sufficient to obliterate long-term pedogenic processes even though horizon differentation may be weakly expressed. In the following sections, pedoturbation, differential loading and soil mechanics, (e.g. three models for Vertisol pedogenesis) will be discussed and evaluated.

Pedoturbation Model

Simply stated, the pedoturbation or self-swallowing model of Vertisols states that as a moist clayey soil with a high shrink-swell potential dries, large

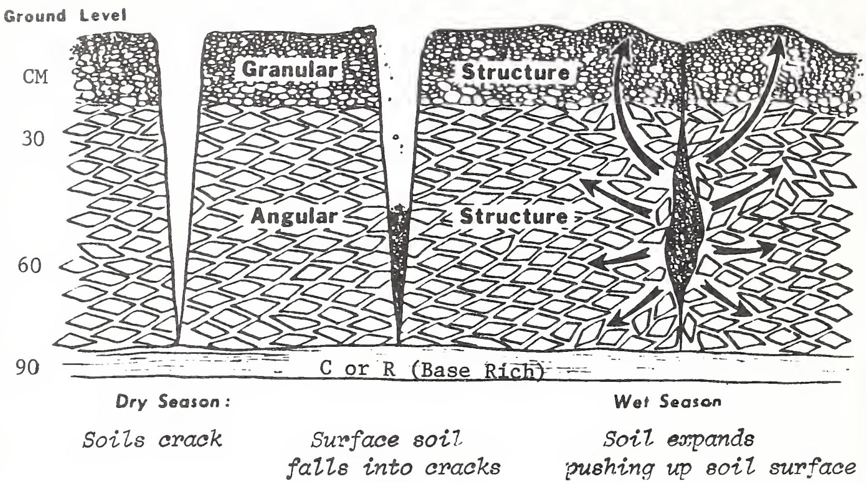

Fig. 1: Pedoturbation or self-swelling model of structure, slickenside and gilgai formation in Vertisols. (From Fig. 16.3, Buol, et al., 1980, page 235).

cracks develop and are infilled with surficial and sidewall material (Fig. 1). Upon re-wetting, swelling of entrained material and adjacent subsoil generates a space problem. Swelling pressures are relieved by oblique and upward shifting of the subsoil to accommodate the space occupied by the infilled crack material. This model holds that pedoturbation is sufficient to retard or obliterate pedogenic horizonation. Mixing of surficial and subsurface materials by churning and inversion results in slickensides, gilgai microtopography and wedge-shaped, tilted structural units (Hilgard, 1906; Vageler and Alten, 1932; Beinroth, 1965; Hallsworth and Beckmann, 1969; Verster et al., 1973; Buol et al., 1980; Ahmad, 1983). While pedoturbation in Vertisols is a dynamic, partially functional process, it is an incomplete genetic model and fails to adequately account for the following relationships and features commonly observed in Vertisols:

- systematic depth functions of organic carbon, carbonates, and soluble salts (Wilding, 1985; Dasog, et al., 1987 — see Fig. 2);
- systematically increasing depth functions for mean residence times of organic matter similar to other soils not subject to cracking (Yaalon and Scharpenseel, 1972 — see Fig. 3);
- maximum slickenside development below the depth of maximum seasonal cracking and crack infilling (Yaalon and Kalmar, 1978; El Abedine et al., 1971);
- gilgai and pedogenic structure formation that is more rapid (5 to 200 years) than suggested by the rate or total amount of crack infilling (Bremer, 1965; Yaalon and Kalmar, 1978; Parsons et al., 1973; White, 1967; and observations by senior author);
- the occurrence of weakly expressed albic and textural Bt horizons in clayey soils with slickensides in Canada (Dasog et al., 1987) and Verti-

sols in Uruguay (personal communication — Mr. Ruben Puentes, Texas A&M University); and

- horizontally-bedded stratigraphic-marker zones (i.e., shell layers and contrasting sedimentary strata) that are not physically contorted except immediately adjacent to slickenside planes (observations by senior author in Vertisols of Philippines).

The systematic soil-property depth functions, development of eluvial/illuvial horizonation, and slightly perturbed stratigraphic marker zones suggest that pedoturbation is not rapid enough to preclude long-term pedogenic translocation processes. One would expect distinct discontinuities in the depth functions of soil properties and mean residence time of organic matter if mixing functions in the upper sola were as dynamic as commonly considered. The lack of confining pressures for materials undergoing swelling in cracks and the long

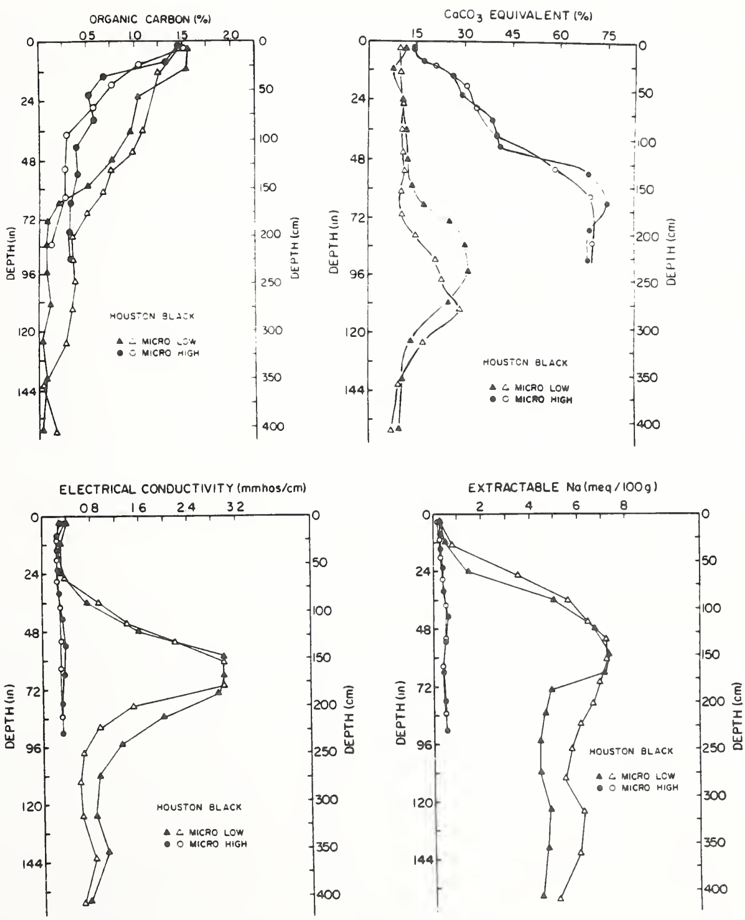

Fig. 2: Depth functions for organic carbon, $CaCO_3$ equivalent, extractable Na, and electrical conductivity for microlow versus microhigh gilgai elements of a Houston Black (Udic Pellustert).

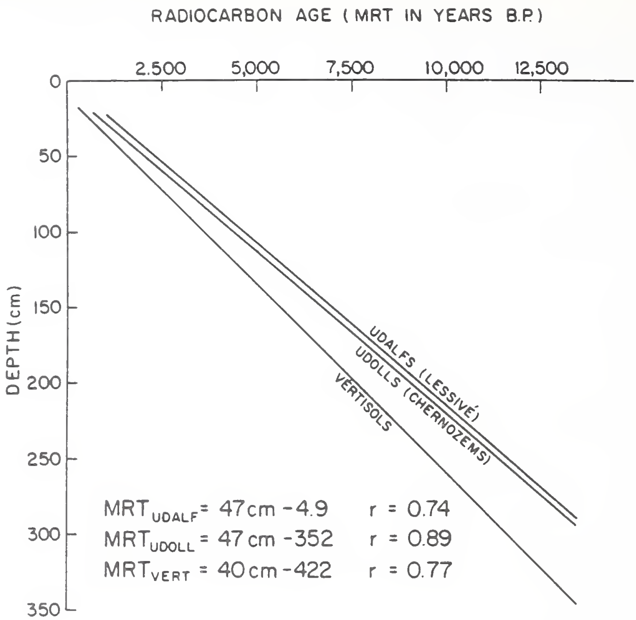

Fig. 3: Regression equations for mean residence radiocarbon age (MRT) of organic matter with depth for Udalfs (N=86), Udolls (N=122) and Vertisols (N=271). Taken from Fig. 8, Yaalon and Kalmar (1978).

hysteresis effects associated with crack closures also discredit pedoturbation as the major process model.

While crack infilling occurs in Vertisols, it does not seem reasonable to argue that this mechanism is primarily responsible for gilgai relief, slickenside formation and cyclic horizonation. At best it is only a partially functional model.

Differential Loading Model

This theory argues that gilgai in Vertisols results from a process whereby clays move from areas of higher confining pressure to areas of lower confining pressures (Paton, 1974). It is basically a plastic extrusion process. Soils with differing thicknesses and densities exert differential pressures upon an underlying plastic subsoil or substratum. This model has been borrowed from the geologic literature for sedimentary load structures (Morgan et al., 1968; Gustavson, 1975). The driving mechanism results from large disparities in densities of two adjacent materials.

The "chimney" or "diapir" structures which protrude to the surface in microhighs from subjacent materials would appear to support this plastic extrusion model (Newman, 1983, 1986). Differential wetting and drying between micro-low and micro-high gilgai elements have been used to support the argument that differential densities and plasticities occur within these soils. How-

ever, the analogy of gilgai formation to sedimentary loading is questionable for the following reasons:

- The regularity of the gilgai pattern does not seem compatible with processes causing density differences in sedimentary loading models (Blokhuis, 1982).
- Marked density differences have not been observed between adjacent horizons or among gilgai elements in Vertisols sampled at the same time (Gustavson, 1975).
- Geological sedimentary loading structures have formed on depositional slopes; the structures tend to be elongated transverse to the slope direction while linear gilgai is commonly oblique or parallel to the slope direction (Gustavson, 1975).

Soil Mechanics Model

A third model for Vertisol pedogenesis, and especially the formation of slickensides, is failure of soil materials along shear planes (slickensides). This occurs whenever the swelling pressures of soil material in a confined system exceed the shear strength of the soil at a specified moisture content (Howard, 1932, McCormack and Wilding, 1974; Yong and Warkentin, 1975; Yaalon and Kalmar, 1978; Knight, 1980; Ahmad, 1983; Wilding and Hallmark, 1984; and Wilding, 1985). This model has been described as a viable alternative for the formation of many Vertisols the senior author has observed and described in detail elsewhere (Wilding, 1985). Much of the discussion that follows has been taken from this source.

The shear strength of a soil is a function of cohesion plus the angle of internal friction. Cohesion is a function of bulk density, clay content, clay mineralogy, and moisture content (McCormack and Wilding, 1979), while the angle of internal friction is related to abundance, roughness, and interlocking of skeleton grains. Upon swelling, a soil is acted upon by two sets of stresses — vertical and lateral (Fig. 4). When the vertical stresses are confined and lateral stresses exceed the shear strength of the soil, failure occurs along a grooved shear plane theoretically at 45 degrees to the horizontal, less ½ the angle of internal friction (Fig. 4). The angle of internal friction would be relatively small for Vertisols because skeleton grains are widely spaced and not interlocked. In practice such shear failure may range from 10 to 60 degrees (Smart, 1970; Knight, 1980).

Consider a dry soil that is rewetting. The wetting front takes place downward from the self-mulching surface horizons and upward from lower solum via tapered cracks initially filled with water (Blake et al., 1973). Absorption of water, swelling, and expansion of the surficial horizons is relieved by upward movement of the surface. However, in the subsoil overburden pressures confine vertical movement and lateral swelling is resolved by crack closure and subsequent development of swelling pressures that exceed the soil shear strength. Swelling pressures in Vertisols are of the order of 1 to 5 kg/cm^2 (Komornik and Zeitlin, 1970; Gustavson, 1975), but shear strengths at moisture contents when failure is most probable are less than 1 kg/cm^2. Lateral swelling pressures may often exceed vertical swelling pressures by a factor of 4 or more (Yong and Warkentin, 1975; Komornik and Zeitlin, 1970).

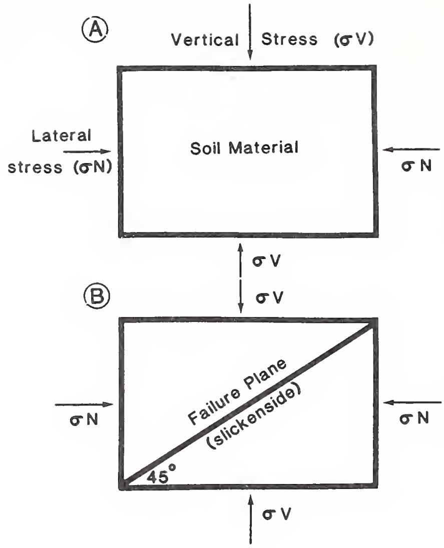

Fig. 4: Soil mechanics model of slickenside formation when confining stresses exceed soil shear strength: (A) Vertical and horizontal stresses acting on a soil ped, and (B) Orientation of shear plane at 45° to the principal stress.

Upon shearing, soil materials are translated along slickenside glide planes. Blokhuis (1982) and Ritchie et al. (1972) have suggested that slickensides near the base of the solum and along the wavy A-AC, A-Bk or A-Bw contact (Fig. 5) are continuous from an area below the center of the micro-low towards a higher position below the center of the micro-high. This is also consistent with observations of White and Bonestell (1960) and Dudal and Eswaran (1988). When observed in the third dimension, slickenside patterns of normal gilgai often form cones of revolution (or bowls) with the vertex centered in the microlow (Knight, 1980; Newman, 1986; Wilding, 1985; Dudal and Eswaran, 1988; see Fig. 5). It is postulated that along such oblique shear planes blocks of subsoil and substratum are upthrust and downthrown. During dry seasons a micro-escarpment or fault zone is commonly observed at the perimeter of microlows as they join microhighs.

A similar process may explain linear gilgai, except that the slickenside planes form a corrugated pattern parallel to the slope gradient. Gravity may be an additional force vector. White and Bonestell (1960) suggested the direct effect of gravity on gilgai genesis of the linear type. Beckmann et al. (1973) and Elbersen (1983) have considered the development of linear gilgai on sloping landscapes and conclude they are related to immature rill erosion patterns. Both processes may be involved in their genesis.

It is speculated that slickenside patterns are related to major desiccation cracks that initially formed during seasonal dry periods in the parent material. For normal gilgai, cracks would form a polygonal network similar to those currently found in microlows. Upon rewetting and swelling, oblique slickensides would form inclined to the direction of major principal stress (lateral); soil ma-

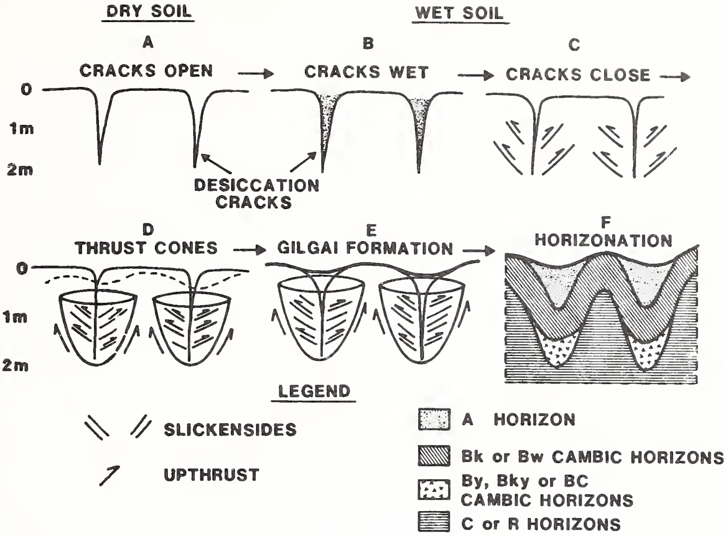

Fig. 5: Schematic illustration of possible stages (A-F) in the formation of slickensides, gilgai and cyclic horizonation.

terial would be translated along these planes. Once initiated, a slightly undulating topography would result and leaching potential would be enhanced in microlows along major desiccation cracks. Leachates would move downward until intercepted by oblique slickenside planes. Then most of the flow would be diverted and effectively funneled to the microlow. Both the topographic relief and slickenside pattern favor development and leaching of microlows while microhighs are renewal sites for subsoil and parent material. Once microrelief is established, desiccation cracks will be best expressed in microlows because they have the highest noncarbonate clay content, undergo the greatest annual extremes in moisture content, and have the highest shrink-swell potential (Blokhuis, 1982). Secondary sets of slickensides form throughout the matrix and at a smaller scale than the major sets of slickenside joint planes. These secondary shear-failures are assumed to occur later in the genetic pathway and as a function of multiple desiccation/wetting cycles.

The proposed stages of gilgai formation are schematically illustrated in Fig. 5 for normal gilgai. This model accommodates the rapid formation of slickensides, pedogenic structure, and normal gilgai relief. It is compatible with systematic depth functions commonly observed in Vertisols and differential intensities of development between microhighs versus microlows (discussed later). Further, it recognizes pedoturbation as a long-term process but one which is not sufficiently dynamic to obliterate the above Vertisol properties. Table 1 summarizes soil properties which support each of these alternative models.

It is postulated that coarse-textured, recent overburden mantling clayey subsoils will decrease slickenside activity and gilgai formation. Such a mantle will effectively serve as a "dust" mulch in breaking the micropore continuity, decrease evaporative potential and decrease subsoil moisture oscillations that

Table 1. Soil properties and features that support (+), do not exclude (+, −) and do not support or may be contradictory (−) to proposed models.

Property or feature	Models		
	Pedoturbation	Soil Mechanics	Differential Loading
Rapid gilgai formation	(−)	(+)	(+)
Crack infilling of surface material	(+)	(+, −)	(+, −)
Slickensides below cracking zone	(−)	(+)	(−)
Radiocarbon age of OM	(−)	(+)	(−)
Systematic depth functions of OM carbonates and salts	(−)	(+)	(−)
Chimneys diapirs of subsurface materials	(−)	(−)	(+)
Disruption of marker strata	(−)	(+)	(+, −)
Formation of E horizons	(−)	(+)	(−)

give rise to maximum shrink-swell potentials. This may partially explain the absence of gilgai relief in ash-mantled landscapes of central El Salvador in spite of evident slickensides in subsoils (Yerima et al., 1987). Alternatively or complementarily, the infrequent number of wet-dry cycles in this seasonally wet-dry ustic climate may hinder gilgai formation.

Knight (1980) using structural analysis has comprehensively evaluated possible origins of gilgai. While many of the soil mechanics attributes of the model proposed in Fig. 5 are consistent with Knight's results, there is one notable exception. Knight (1980) suggests that microhighs form from cumulative internal vertical movements along small oblique slips immediately associated with major crack zones—not between two major crack zones. Arguments proposed for this hydro-mechanical model are observed three-dimensional configuration of slickensides, triaxial shear stresses in a swelling soil and differential moisture concentration surrounding soil cracks.

FACTORS AFFECTING SHRINK-SWELL PHENOMENA

General Considerations

Shrink-swell phenomena in Vertisols can be better understood if approached from a basic understanding of physical-chemical principles in clay-water systems. This body of knowledge is largely gained from reference clay mineral systems. Its transferability to natural soil systems must be made with caution because natural soil fabrics are influenced by external environments. In spite of this limitation, the approach provides a means to conceptualize active shrink-swell processes in Vertisols. The following discussion focuses on properties of soils which are recognized as influencing shrink-swell including: soil fabric, mineralogy, saturating cation, electrolyte concentration and speciation, clay content, surface area, antecedent soil moisture content, frequency of desiccation/rewetting cycles, confining pressures, and soil thickness. Other factors affecting shrink-swell include macro- and microclimate, slope, topography, vegetation, cropping patterns, and soil management practices.

Soil Fabric

Shrink-swell is decreased by chemical or physical components, such as organic matter, carbonates, sesquioxides (Fe and Al), silica, and low activity clays, which bind or cement the soil fabric. These plasma components increase fabric cohesive forces. Likewise, interlocking of soil skeleton (sand and silt) grains will increase the frictional forces and decrease shrink-swell. The orientation of clay particles or clay aggregates in the fabric either as an expression of pedogenic processes or sedimentation may markedly influence shrink-swell and provide markers of past shear failure (Fig. 6). Much is yet to be learned about microfabric impacts on shrink-swell phenomena (Parker, et al., 1980, 1982). These authors observed that entrapped air pressures upon rewetting compacted soils also postively impacts swelling.

Clay Content and Specific Surface Area

Shrink-swell phenomena in soils are related to total and fine clay contents, especially in 2:1 and 2:2 layer clay mineral systems. Vertisols are noted for their high clay contents, high fine clay content (<0.2 um) and high shrink-swell potential. Coefficients of linear extensibility (COLE) values range from 0.1 to 0.2 or higher). This reflects their smectitic and other fine-grained ex-

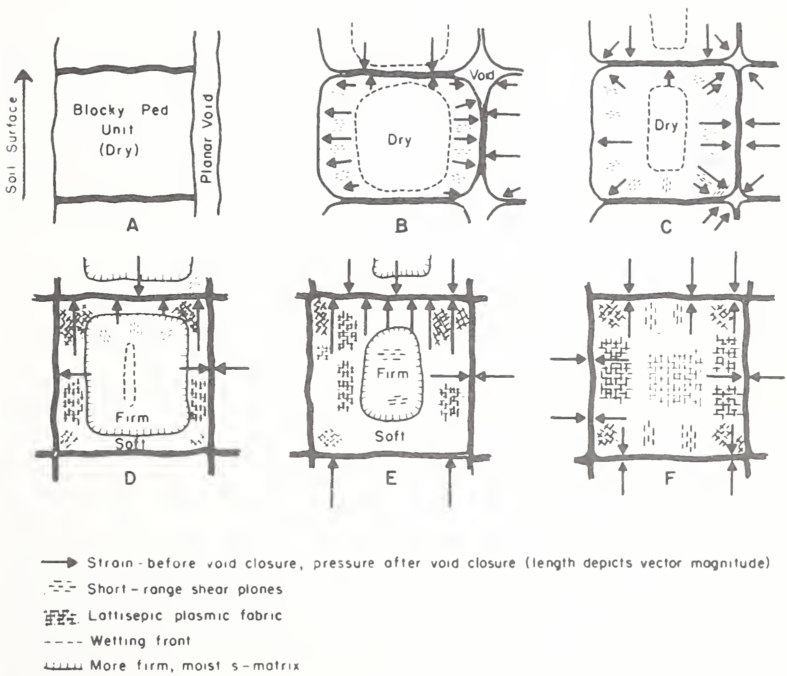

Fig. 6: Schematic illustration of proposed origin for stress — oriented plasmic fabrics found within structural units of Vertisols. Microshear generates masepic, skelsepic and lattisepic plasmic fabrics. (Taken from Fig. 5, McCormack and Wilding, 1973).

pandable 2:1 clay mineral components (Dixon, 1982). Surface area, particularly external surface area, is very closely correlated with shrink-swell potential (McCormack and Wilding, 1979; Yerima, et al., 1988). Hence, the higher the percentage of fine clay materials, the higher the surface area and shrink-swell potential.

Soil Moisture Content

The antecedent soil moisture contents are very important in shrink-swell. The greatest swelling pressures are achieved when the soil undergoes maximum change from dry to wet conditions. Likewise, the greatest shrinkage occurs when the soil dries from near saturation to the shrinkage limit (Tessier, 1980; Tesssier and Pedro, 1980; Yule and Ritchie, 1980). An increased frequency of desiccation-rewetting cycles enhances the expression of slickensides and gilgai. Consequently, gilgai is often best expressed in ustic (semi-arid) and in ustic-udic intergrade (sub-humid) climatic regions. Parker et al. (1982) observed increased swelling with repeated wet-dry cycles on undisturbed and compacted soil samples. Considerable differences were observed among soils in swelling as a function of initial moisture content.

Confining Pressure

Observed field volume changes in soils are commonly less than the COLE values would predict. This is because of lateral and overburden confining pressures. McCormack and Wilding (1975) observed that a confining pressure equivalent to 10% of the swelling pressure can reduce the percent swell by half. Conversely, decreasing the confining pressure by an amount equal to 10% of the swelling pressure could double the percent swell. Hence it takes a relatively small amount of overburden pressure (soil thickness) to result in a significant reduction of the percent swell in a given horizon.

Microclimate and Management Factors

Microclimatic conditions between gilgai elements, such as seasonal soil moisture patterns, also markedly influence shrink-swell activity. Based on field soil moisture observations, leaching profiles, and patterns of vegetation, the maximum oscillation between wet and dry soil conditions is manifested in microlows. Vegetation in microlows is able to extract water to greater depths and at lower matric potentials than in microhighs. Noncarbonate clay contents and specific surface areas are highest in microlows. Thus, the highest shrink-swell potential would be expected to occur in microlows. This is, in fact, substantiated by expression of the widest and deepest cracks, maximum swelling pressures, highest frequency of slickensides and predicted maximum changes in surface elevation.

Different kinds of cropping patterns, tillage systems and irrigation practices which govern moisture contents and water extraction patterns also markedly influence shrink-swell (Ahmad, 1983; Kalmar and Yaalon, 1986).

Clay Mineralogy

Greene-Kelly (1974) observed that shrinkage is usually positively correlated with expansible mineral content. He found, however, that soils with equal amounts of kaolinite and montmorillonite were similar to those with montmorillonite alone. Observations of El Salvador Vertisols (Yerima et al., 1985, 1987) indicated that kaolinite-rich, fine-clay systems have similar physical behavior to smectitic ones because of their large surface area. The dependency of COLE on type and amount of clay also has been recognized by Franzmeier and Ross (1968) and by Smith et al. (1985). They observed the highest COLE values in soils with high clay contents dominantly of the smectite type.

The following discussion pertains primarily to 2:1 and 2:2 layer clay mineral systems. It describes the influence of clay mineralogy on shrink-swell phenomena in soils and is based heavily on the work of Tessier (1984), Tessier and Pedro (1982), Tessier and Berrier (1979), Pons et al. (1982), Halitim et al. (1984), Ben Rahiem et al. (1987), Tessier and Pedro (1987), and Parker et al. (1980, 1982). The clay mineral properties that influence shrink-swell include layer charge, water of hydration, interlayer properties, microstructure, interparticle porosity, and clay particle flexibility and extensibility.

In this discussion terms are defined as follows:

(i). *Clay layer* — the elementary unit of structure comprised of stacked units of tetrahedral and octahedral sheets forming the given clay mineral unit cell.

(ii). *Interlayer* — the space between successive stacked elementary layer units.

(iii). *Clay particle* — secondary microstructural domains formed by face-to-face stacking of elementary clay layer units into compound tactoid, quasicrystal or plasma aggregate units.

(iv). *Interparticle porosity* - the pore space associated with the microstructural network of substacked particles. This porosity consists of two elements: (a) space between stacked quasicrystals comprising clay particles (function of the number of layers in a particle) and (b) space between inter-particle pores of the microstructural domains (function of orientation of quasicrystals).

Charge Deficiency

Most layer clay minerals are electrically unbalanced because of isomorphic subsitution of lower valence cations for Si or Al in silica and alumina sheets, respectively. This charge deficiency is compensated by interlayer counter cations. The magnitude and location of charge deficiency governs clay mineralogy, interlayer cation, interlayer cation exchange properties, water of hydration, particle flexibility, extensibility of overlapping particles, interparticle porosity, specific surface area, and nature of microstructural units forming clay particles. All of these clay mineral attributes influence shrink-swell properties of soils under given soil environments.

Clays with the lowest charge deficiency have the highest degree of hydration (Fig. 7), most complete interlayer exchange (Fig. 8), the most flexible clay

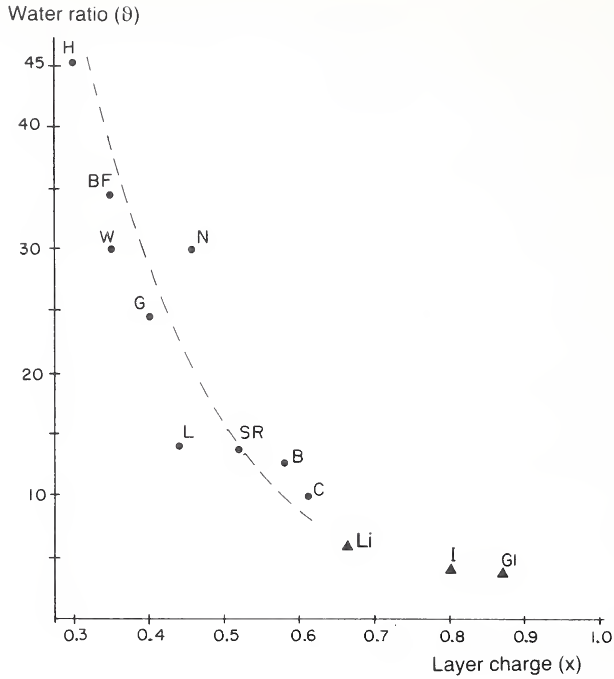

Fig. 7: Inverse relationship between layer charge deficiency (per unit half cell) and water ratio (θ) of 2:1 layer clays in 10^{-3} *M* NaCl at -0.032×10^5 Pa (0.032 bar suction). Smectites (H-hectorite, BF-Belle Fourche, W-Wyoming, G-Greek, L-Lorena, SR-Santa Rita, B-Bethonvilliers, C-Cameron) and micas (Li-Licheres, I-Le Puy illite, GI-glauconite). (θ = water volume/particle volume).

particles and exhibit the greatest shrink-swell potential (Tessier, 1984). Those with charge deficiencies less than about 0.45 per unit half cell exhibit complete interlayer exchange and have swelling characteristics of smectites (Fig. 8). Those clays with charge deficiencies between 0.45 and 0.6 have incomplete interlayer exchange and x-ray diffraction spectra of irregular interstratified smectite/mica assemblages. Clays with higher charge deficiencies (above 0.6 per half cell) are mainly micas, have less interlayer expansion, have fewer interlayer cations that are exchangeable (K is fixed in selective interlayer positions), have more brittle layers and exhibit less extensive lateral overlap of particles in the ab-plane.

Microstructure

Microstructures of clay/water systems appear to control the shrink-swell properties of soils under natural environmental conditions. Figure 9 depicts such microstructures for smectites at near saturation (-0.032 Pa x 10^5 or 0.032 bar suction) and under low electrolyte concentrations (10^{-3} M) of NaCl and $CaCl_2$.

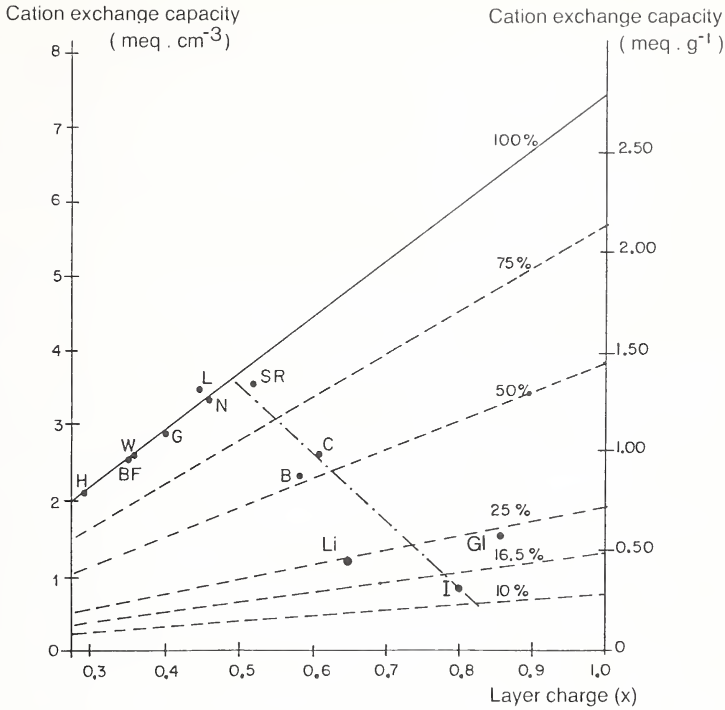

Fig. 8: Relation between cation exchange capacity and layer charge deficiency of 2:1 clays. Diagonal lines indicate the proportion of exchangeable interlayer cations. Smectites (H-hectorite, BF-Belle Fourche, W-Wyoming, G-Greek, L-Lorena, SR-Santa Rita, B-Bethonvilliers, C-Cameron) and micas (Li-Licheres, I-Le Puy illite, and GI-glauconite). Taken from Tessier, 1984).

Na-smectites: At low electrolyte concentration the microstructure of Na-smectites is schematically illustrated in figure 9A. The microstructure consists of interparticle pores less than 1μm diameter filled with water. The interparticle pore walls consist of laterally extensive, overlapping clay particles (quasicrystals). Each of the quasicrystals consists of 5 to 10 layers of clay stacked face to face in the ab-plane that overlap into laterally extensive clay particles of about 500 nm in length (Fig. 10). Note the interparticle pores of 50-100 nm diameter between staking planes of quasicrystals. Each of the layers has a d-spacing ranging from about 3.5 to 10 nm (35 to 100A) in thickness. The interlayer is hydrated, forming a diffuse double- layer structure. As the layer charge on the clay increases, the water content of the clay decreases and the number of layers comprising a quasicrystal increases. This results in less flexible and less laterally extensive quasicrystals that form more rigid microstructures less conducive to shrink-swell. It thus requires more energy to open and close these microstructures.

Ca-smectites: At low electrolyte concentration the microstructure of Ca-smectites is schematically illustrated in figure 9B. The general organization is similar to that of Na-smectites but differs in three important ways. First, the interparticle pores are larger, with dimensions ranging from about 1 to 2 μm

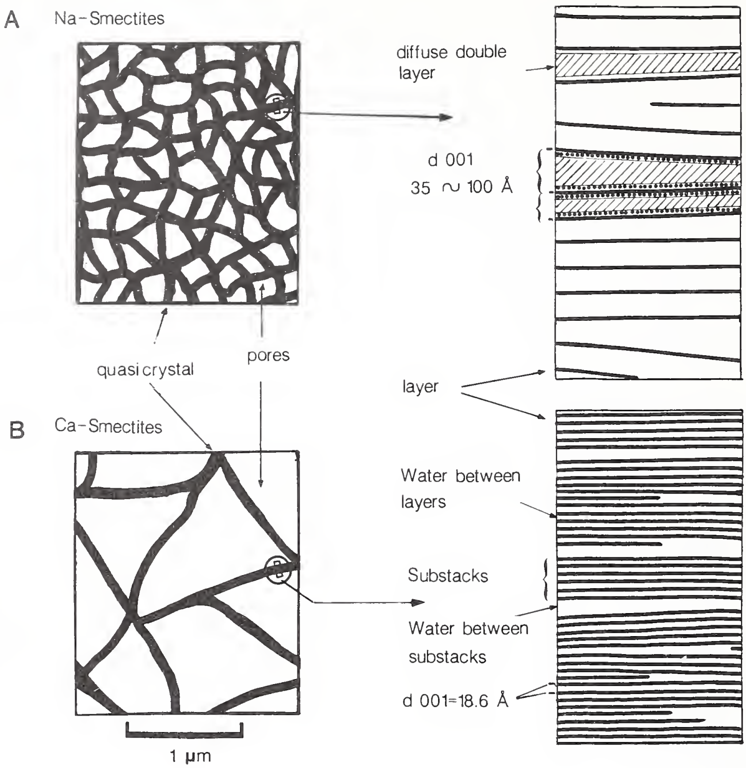

Fig. 9: Schematic representation of the microstructure of Na-smectites (A) and Ca-smectites (B) prepared in low electrolyte concentrations of chloride solutions (10^{-3} *M*).

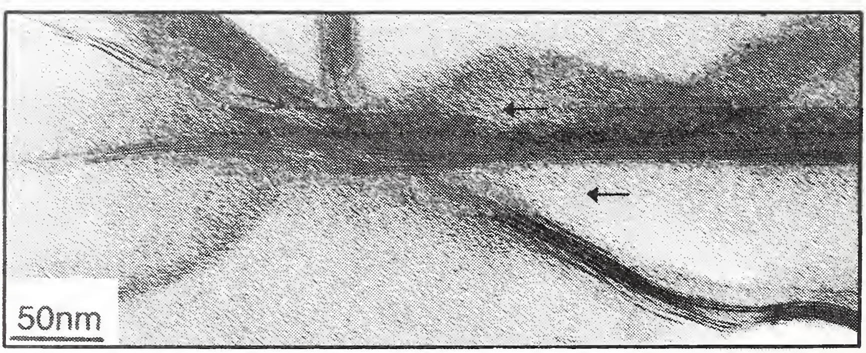

Fig. 10: Transmission electron lattice imagery of Na-hectorite in 10^{-3} *M* NaCl solution at -0.032 × 10^5 Pa (0.032 bars suction) matric potential. Note 5 to 10 layers stacked face to face into clay particles. Interparticle pores (arrows) between stacked quasicrystals).

in diameter. Secondly, the diffuse double-layer structure for clays comprising pore walls is absent. Interlayer water is limited and the d-spacing for individual layers is only about 1.86 nm (18.6 A). Thirdly, the number of layers comprising a clay particle is generally 50 or more (Fig. 11) and thus the layers are less flexible than for low electrolyte Na-smectite systems. Interparticle porosity is again evident between successive quasicrystal stacks. Mg-smectites and high electrolyte (1 *M* NaCl) Na- smectites behave like Ca-smectites.

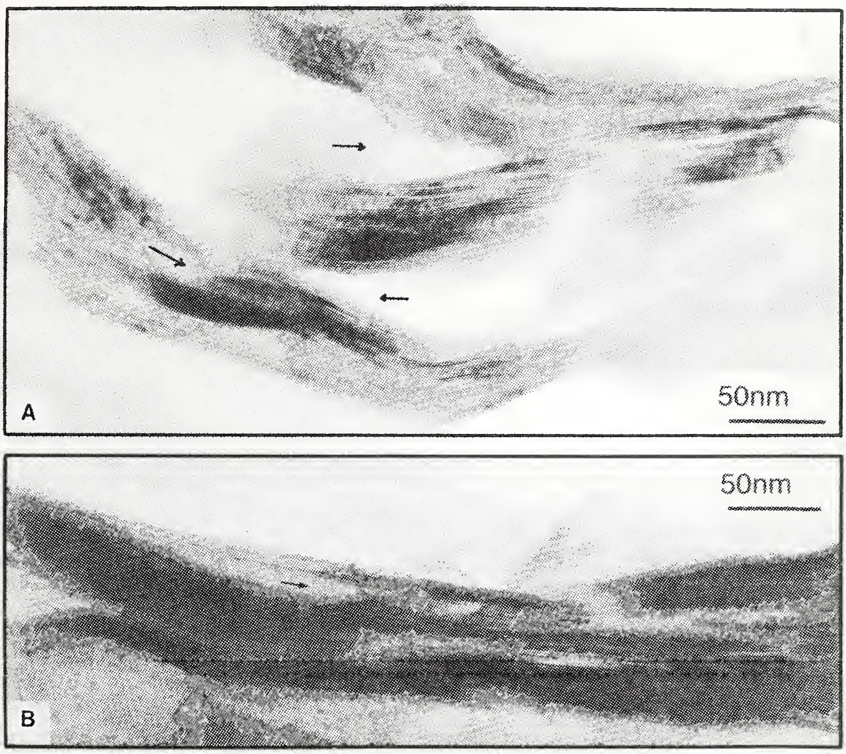

Fig. 11: Transmission electron lattice imagery of (A) Greek Na-smectite in 1 *M* NaCl solution, and (B) Greek Ca-smectite in 10^{-3} *M* $CaCl_2$ solution at -0.032×10^5 Pa (0.032 bars suction) matric potential for both. Note interparticle pores (arrows — between stacked quasicrystals).

Figure 12 illustrates schematically relative swelling volumes of smectites, illites and kaolinites as a function of electrolyte concentration, cation speciation, microstructure and matric potential. It should be noted that the term high matrix potential refers to soils with high water contents (low suction values), and low matric potential to low water contents (high suction values). This figure demonstrates that at high matric potential [-0.01 to -1.0 Pa x 10^5 (0.01 to 1 bar suction)] the shrink-swell potential in decreasing order is: Na-smectites > Ca- and Mg-smectites > Ca-, Mg- and K-illites > kaolinites. The role of cation speciation is noted for smectites where low electrolyte Na- saturated systems have more than twice the shrink-swell potential of Ca- and Mg-

smectites. The impact of microstructure on shrink-swell is also apparent for illite and kaolinite. Here the brittle, rigid domains of illite and large crystallites of kaolinite do not favor flexible, extensive, overlapping quasicrystals as is true for smectites. Thus, the shrink-swell volume changes for illite and kaolinite clays are only about ½ to ⅕ that of smectites. Further, smectitic clay systems at low matric potential [-1000 Pa x 10^5 (1000 bars suction)] occupy less volume per unit weight than illitic and kaolinitic counterparts. This is because the interparticle porosity of smectite completely collapses at this low matric potential, whereas for illite and kaolinite clays porosity remains — domains and large crystals do not completely accommodate each other because they do not overlap into quasicrystals.

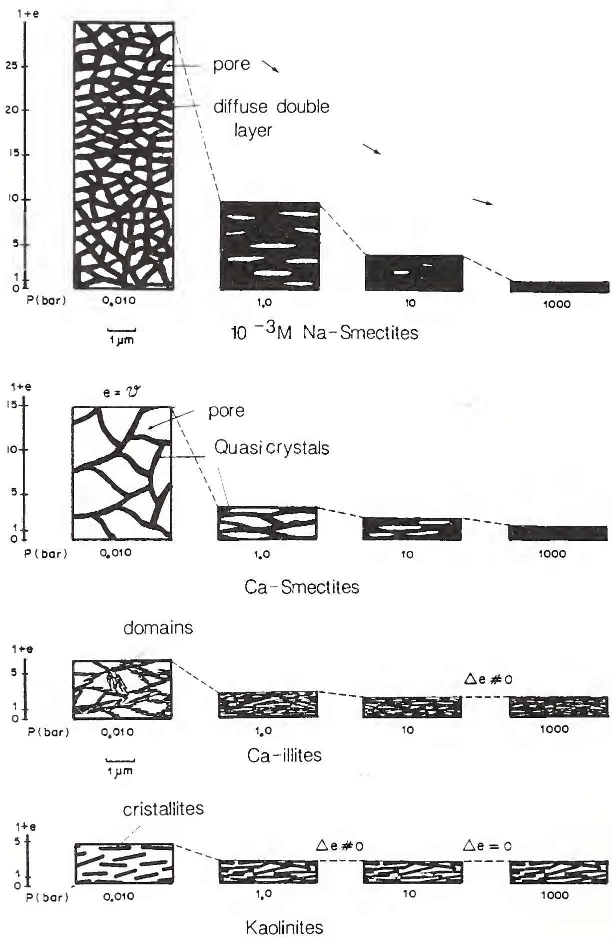

Fig. 12: Schematic illustration of relative swelling and consolidation volumes as a function of matric potential. (e = void ratio — the volume of pore space to solid particle volume)

Contrary to popular belief, interlayer hydration-dehydration does not appear to be an adequate model to explain shrink-swell phenomena under field conditions. Only for the Na-saturated, low electrolyte smectitic clay systems illustrated in Fig. 9A is the diffuse double-layer model likely to be functional (Tessier, 1984). However, for most calcareous Vertisols which also demonstrate extensive shrink-swell potential, a model based upon changes in interparticle porosity is much more functional (Fig. 9B). Attributes of layer charge, layer flexibility and extensibility of overlapping layers are considered to be the most important.

Electrolyte Concentration and Speciation

As eluded to in the preceding section, electrolyte concentration and speciation may markedly affect shrink-swell behavior of smectites. Low electrolyte Na-smectites reflect one behavioral system (Fig. 9A). In this system, both interparticle pore water and a portion of the interlayer water contribute to field volume changes with changing soil moisture content. However, for high electrolyte Na-smectites, and Ca- and Mg-smectites (Fig. 9B) of either high or low electrolyte concentration, only interparticle pore water contributes to field volume changes (Tessier, 1984; Pons et al., 1982; Tessier and Pedro, 1982).

The importance of electrolyte concentration and speciation should be considered in evaluating sodium adsorption ratio (SAR) and exchangeable sodium perecentage (ESP) relative to clay dispersion. Under low electrolyte systems, clays may be dispersed at relatively low SAR's and ESP's (5 to 8% or less), while in higher electrolyte systems, ESP's of 15% or more may be required. Further, gypsum in a system will surely promote flocculation of clays and lower shrink-swell potentials independent of SAR or ESP values. Thus, a sliding ESP (or SAR) vs EC scale is necessary to accurately predict probable clay dispersion in soil fabrics.

Coupled with other microstructure and clay mineral effects, electrolyte concentration and speciation represent important soil determinants that control shrink-swell potential of Vertisols and consequently gilgai and cyclic horizonation.

Soil Shrinkage Phenomena

Examination of volume changes in clayey soils as a function of water loss reveals three shrinkage phases (Fig. 13) (Yule and Ritchie, 1980). The initial loss of water from stable macropores results in little or no volume change — *structural porosity.* With continued water loss between the swelling limit and the shrinkage limit, volume change is a function of water loss from interparticle pores (Fig. 9) — *shrinkage porosity.* This portion of the shrinkage curve is linear, equidimensional and normal (Yule and Ritchie, 1980). This means that for each volume of water lost from interparticle pores, one unit volume of shrinkage occurs in all directions at approximately 90° to x, y and z axes. One would not really expect the shrinkage to be normal, equidimensional and linear unless the soil fabric consisted of randomly oriented clay domains. This is clearly not true in these Vertisols, but because preferred orientation of clay

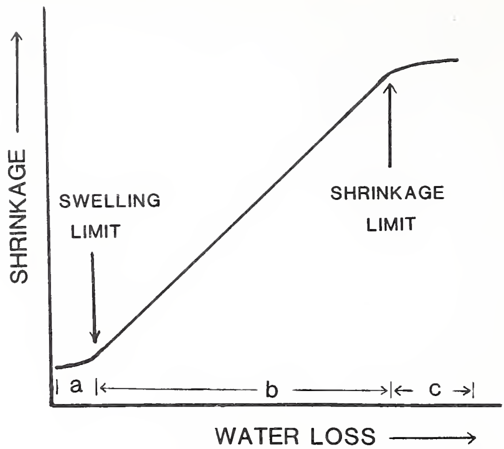

Fig. 13: Schematic shrinkage curve illustrating swelling limit and shrinkage limit and porosity phases (a) structural, (b) normal shrinkage, and (c) residual.

particles is within primary micropeds (frequently 1 mm or less in diameter) that are distributed at random, then measurements as observed by Yule and Ritchie (1980) are reasonable. With further water loss beyond the shrinkage limit there is no appreciable volume change. The shrinkage that occurs at these low soil matric potentials is due primarily to interlayer water and water of cation solvation — *residual shrinkage.*

The above model is functional for all clay-water systems except the low electrolyte Na-smectitic systems. In the latter case, the linear portion of the shrinkage curve reflects both water loss from interparticle and interlayer porosity.

Dehydration — Rehydration

Quantification of the pore system contributing to shrink-swell phenomena can be obtained by determining low angle x-ray scattering effects and d-spacings of clays and associated microstructures under decreasing matric potentials from near saturation to -1000 Pa x 10^5 (1000 bar suction) (Ben Rahiem et al., 1987).

For example, dehydration of Mg- and Ca-smectites results in interlayer waterloss only at matric potentials lower than -50 Pa x 10^5 (50 bars suction) (Tessier, 1984). The d-spacing of these clay/water systems remains at 1.86 nm (18.6A) until the matric potential decreases below -50 Pa x 10^5 (50 bars suction); at -1000 Pa x 10^5 (1000 bars suction), one molecular layer of water is removed and the d-spacing decreases to 1.56 nm (15.6A) (Table 2).

At less than -1 Pa x 10^5 (1 bar suction), the average number of layers comprising a quasicrystal is 55 and is not affected by matric potential (Table 2). At -10 Pa x 10^5 (10 bars suction) the number of layers increases to 225, and at -1000 Pa x 10^5 (1000 bars suction) the average number of layers forming a particle increases to 400. This suggests that the water behavior and shrink-swell potential are related essentially to change in particle size (texture) and arrangement of particles comprising interparticle porosity. Desiccation changes

Table 2. Dehydration and rehydration of Wyoming Ca-smectite under low electrolyte (10^{-3} M) $CaCl_2$ solutions (after Ben Rahiem, et al., 1987)

Matric potential (Pa × 10^5) (bars)	Layers comprising clay particle	Layer d-spacing (nm)	Water Content (g H_2O/g clay)
	Dehydration (1st drying)		
0.033	55	1.86	4.90
1	55	1.86	1.28
10	225	1.86	0.60
1000	400	1.56	0.23
	Rehydration		
10 → 0.033	65	1.86	1.60
10 → 1	65	1.86	0.92
1000 → 0.033	90	1.86	1.10
1000 → 1	170	1.86	0.60

the configuration of the microstructure, orientation of clay particles and surface area of quasicrystals (clay particles). Thus, particle size is a temporal property dependent on changes in matric potential and consequent hysteresis effects. Similar behavior and structure changes have been observed for Na-smectites in the presence of high salt contents (Tessier and Pedro, 1982; and Tessier, 1984).

For low electrolyte Na-smectites, the d-spacings at -1×10^5 Pa (1 bar suction) are about 10 nm, (100 A). When the matric potential is decreased to -10×10^5 Pa (10 bars suction), a part of the interlayer diffuse double layer water is removed and d-spacings occur at both 3.5 and 2.0 nm (35 and 20 A) suggesting the coexistence of a gel phase (3.5 nm) and a hydrated solid phase (2.0 nm). Further decrease in matric potential to -25×10^5 Pa (25 bars suction) increases loss of water from the gel phase and enhances the 2.0 nm d-spacing.

The interlayer loss of water with decreasing matric potential, even up to -1000×10^5 Pa (1000 bars suction), results in minimal change in particle size; the number of layers comprising a quasicrystal increases only from about 8 to 20. Further, rewetting a dried sample of low electrolyte Na-smectite is completely reversible at matric potentials of -10 to -25×10^5 Pa (10 to 25 bars suction) and hysteresis effects on particle size and hydration state are minimal up to -1000×10^5 Pa (1000 bars suction) (Tessier, 1984; Ben Rahiem et al., 1987).

The increase in particle size and preferred orientation of particles with desiccation and dewatering of the microstructures and consequent hysteresis effects are more marked for the Ca- and Mg- smectites than for low electrolyte Na-smectites (Figs. 14-15, and Table 2). For example, after drying a Ca- smectite to successively lower matric potentials of -0.1, -1, -10 and -1000 Pa x 10^5 (0.1, 1, 10 and 1000 bars suction), rehydration is only partially reversible (Fig. 14). The greater the desiccation before rehydration the greater the hysteresis effect. When dried to -1000 Pa x 10^5 (1000 bars suction), rehydration results in a water content of less than 30% of the original undried clay (Fig. 14). Similar effects are found for micaceous clays. This hysteresis effect was much less pronounced for the Na-smectite under low electrolyte concentration (Fig. 15). Here, rehydration resulted in a water content of about 70% of the undried original clay.

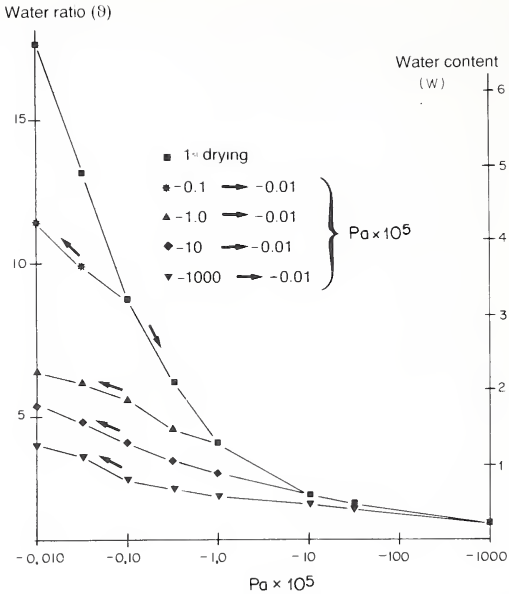

Fig. 14: Water ratio (θ) and water content (w) as a function of dehydration of Wyoming Ca-smectite in a 10^{-3} M $CaCl_2$ solution from -0.01 to -1000×10^5 Pa (0.01 to 1000 bars suction) and subsequent rehydration. (θ = water volume/particle volume)

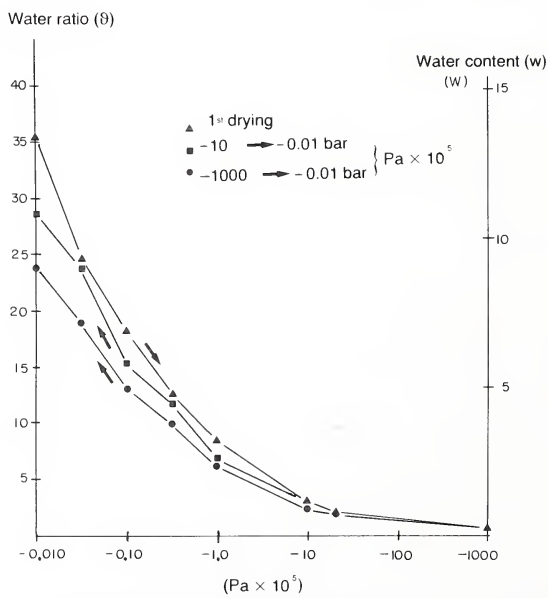

Fig. 15: Water ratio (θ) and water content (w) as a function of dehydration of Greek Na-smectite in a 10^{-3} M $CaCl_2$ solution from -0.10 to -1000×10^5 Pa (0.10 to 1000 bars suction) and subsequent rehydration. (θ = water volume/particle a volume)

In summary, the hydration properties of clay materials are related to the maximal stress applied to the material in the past. This maximum stress may be of climatic or geostatic origin. It represents what is referred to in soil mechanics as consolidation pressure. Consequently, the hydration and swelling properties of clay materials cannot be related solely to the water potential of the system. It is also necessary to consider the stress history of the material.

The impact of dehydrating a Na-smectite of high electrolyte content (1*M* NaCl) on microstructure and interparticle porosity is illustrated in Figure 16. At near saturation [-0.032 Pa x 10^5 (0.032 bar suction)], the microstructure is honeycombed. Clay quasicrystals form pore walls with interparticle pores of about 2 μm in diameter. Upon slight desiccation [-1 x 10^5 Pa (1 bar suction)], the loss of water from interparticle pores results in increased capillary water tension. The interparticle pores become lenticular in shape (flattened). The quasicrystals forming the pore wall fold on top of each other in a face-to-face ab-plane orientation. The above effects become more marked as soil moisture stress increases to -10 Pa x 10^5 (10 bars suction). Under this condition most of the interparticle pores are obliterated and the shrinkage limit is approached. We would expect similar results with Mg- and Ca-smectitic clays.

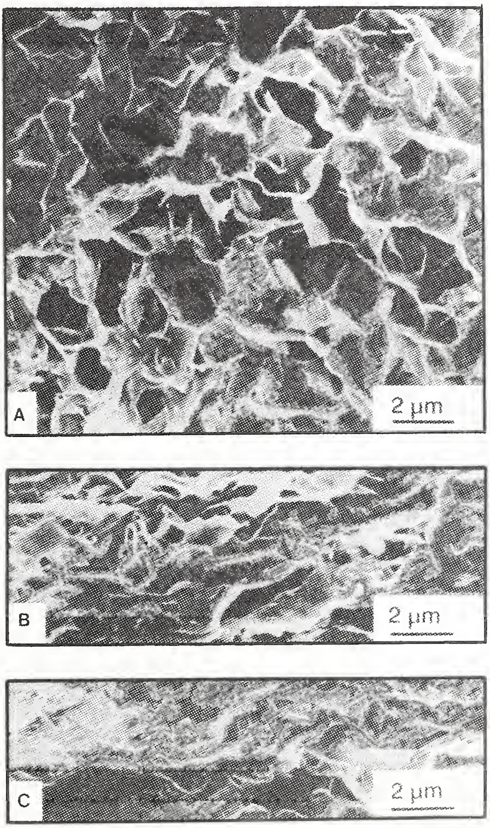

Fig. 16: Microstructure of Greek Na-smectite under high electrolyte concentration (1 *M* NaCl): (A) at near saturation — -0.032 Pa $\times$ 10^5; (B) after drying to matric potential of 1×10^5 Pa; and (C) after drying to matric potential of 10×10^5 Pa.

Similar SEM micrographs of changes in microstructure upon desiccation were obtained for a natural soil fabric of a Vertisol (Fig. 17). This demonstrates that the principles for shrink-swell discussed above for clay-water systems also apply to natural soil fabrics.

Expansion and contraction of the clay microstructure can be visualized as an accordion. When the soil is at the swelling limit the accordion is open and the bellows are filled with water. As the soil dries below the swelling limit, water is lost from between the bellows and the accordion begins to close. Upon rehydration, water re-enters the bellows, pore water pressure increases and the bellows of the accordion open. The degree to which the soil shrinks and expands depends on the initial water content, the thickness and size of the bellows, and the composition of the bellow material — the resistance of the bellows to open and close. The less flexible and less extensive the bellows (quasicrystals), the higher their resistance to volume changes. Hence, the greater the resistance to change interparticle geometry, the higher the energy that is required to activate it. In turn increased activation energy lowers the shrink-swell potential of the soil system.

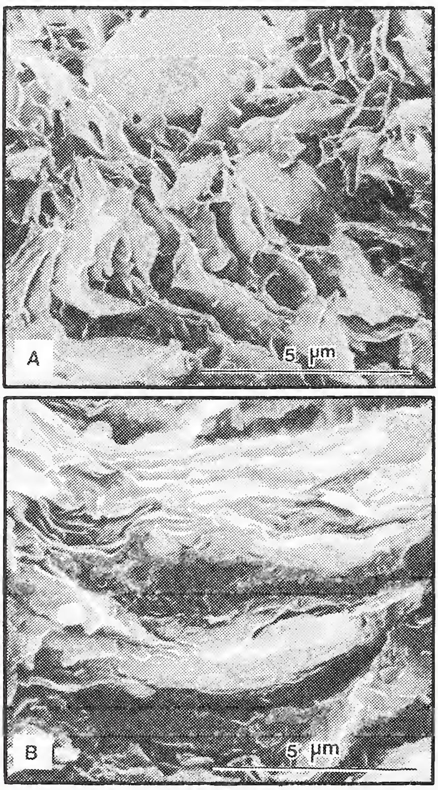

Fig. 17: Microstructure of a Vertisol (A) at near saturation [-0.032 Pa $\times 10^5$ (0.032 bar suction)]; and (B) at matric potential of -1000×10^5 Pa (1000 bars suction). Undisturbed sample from Bethonvilliers (France), 150 km S.W. Paris in Perche area.

With the exception of low electrolyte Na-smectite systems, one can state the following:

- most of the field shrink-swell occurs at high matric potentials — between -.33 and -20 Pa x 10^5 (⅓ to 20 bars suction);
- with few exceptions, shrink-swell is minimally related to loss of interlayer water — interlayer porosity;
- shrink-swell is mostly correlated with water loss and gain between clay particles — interparticle porosity;
- shrink-swell is closely correlated with external surface area — (number and thickness of layers forming pore wall quasi- crystals);
- low-charge smectites have fewer layers comprising quasicrystals, higher external surface area, more flexible clay microstructures, and higher shrink-swell potential than high- charge smectites; and
- shrinkage as observed on field bulk samples is generally normal (90°), undimensional, and linear.

Microfabrics

Swelling processes in soils result in microshear within the soil fabric. Such stresses reorient clay particles into lineated zones with face-to-face clay alignment. These features are easily recognized by SEM (Fig. 18) and in a cross-polarized light mode of a petrographic microscope (Fig. 19). They are permanent markers of historical soil failure. These shear zones reduce the strength of the soil fabric. Often translation of soil materials on failure coincides with previous microshear or slickenside zones. Microfabrics, thus, reflect differential wetting and subsequent swelling of a dry soil fabric. This process enhances structural development, the formation of ped pressure faces

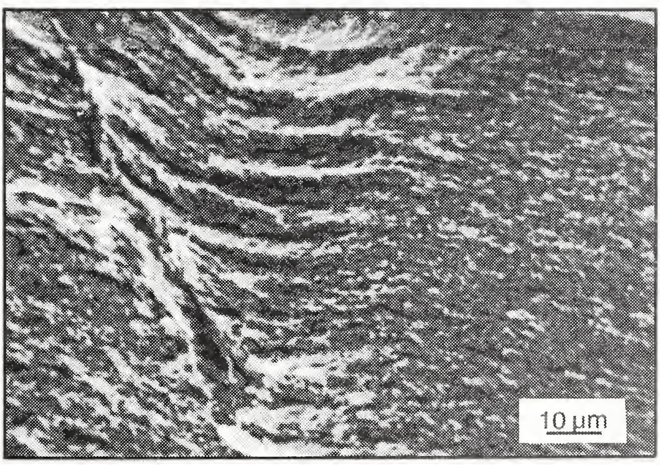

Fig. 18: SEM micrograph illustrating a microshear zone developed in Greek Na-smectite upon rewetting sample previously dried from near saturation to -1000×10^5 Pa (1000 bars suction) matric potential. Electrolyte is 1 *M* NaCl.

and slickensides (McCormack and Wilding, 1974, 1975 and 1979; Wilding and Hallmark, 1984; and Wilding, 1985). Soil fabrics representing different loci, intensity and mechanisms of microshear are characterized by masepic, vosepic, skelsepic and lattisepic plasmic fabrics. Often these stress features are not evident in crystic plasmic fabrics of calcareous Vertisols until special techniques are used to remove the carbonates (Wilding and Drees, 1988).

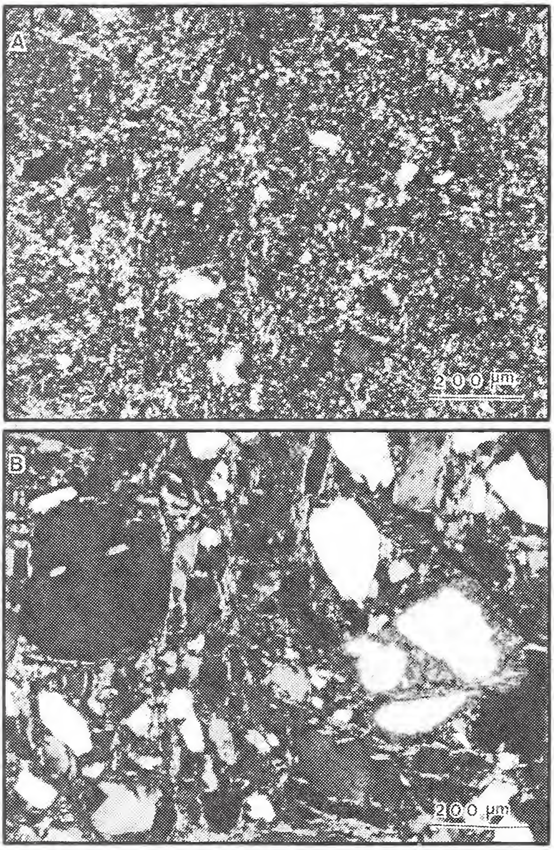

Fig. 19: Thin-section microfabrics of Vertisols in Northern Cameroon illustrating microshear — (plasma separations) for: (A) masepic, and (B) skelsepic plasmic fabrics. Cross polarized light mode.

CONCLUSIONS

Slickensides are the unifying morphogenetic thread common to all Vertisols and to many soils which are classed as vertic intergrades. Shear zones control soil strength on both a macro- and micro-scale. They record the history of soil failure. Pedoturbation, while a functional process in Vertisols, is inadequate to solely account for rapid gilgai formation and slickenside evolution, especially at depths below major cracks.

Shrink-swell phenomena in Vertisols are governed by a large array of soil and non-soil determinants including: geologic parent materials, climate, topography, vegetation, tillage and cropping practices, history of soil moisture stresses, soil texture, clay mineralogy, soil chemistry, and soil fabric. Most volume changes observed under field conditions occur at high matric potentials [-0.33 to -20 Pa x 10^5 (.33 to 20 bars suction)]. With few exceptions, interlayer hydration-dehydration occurs only at very low matric potentials [-100 to -1000 Pa x 10^5 (100 to 1000 bars suction)] not commonly found under field conditions. The one exception is low electrolyte Na-smectitic clays. In these systems interlayer water does contribute to volume changes under field conditions. However, in most clayey soil systems shrink-swell occurs in response to changes in shape and volume of interparticle porosity upon changing hydration state. Desiccation causes corresponding changes in particle size, surface area and particle orientation which are partially reversible upon rehydration depending on history of soil moisture stresses.

The greatest magnitude of volume changes in clayey soils should be expected in soil systems under the following conditions:

- greatest oscillation between wet and dry soil moisture state;
- highest content of total and fine clay;
- highest external specific surface area;
- 2:1 layer clay minerals with lowest charge deficiency; and
- clays with flexible clay layers that are stacked face-to-face in laterally extensive quasicrystal configurations.

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Chapter 5

CHARACTERIZING SOIL WATER REGIMES IN SWELLING CLAY SOILS

J. Bouma and J. Loveday

INTRODUCTION.

Soil water regimes in clay soils are difficult to characterize because swelling and shrinkage processes induce constantly changing pore-size distributions and pore-continuity patterns. Measurement and monitoring techniques that work well in sandy or loamy soils may produce erroneous results in clay soils, as will be illustrated later.

Modern soil survey interpretations are increasingly being focussed on defining soil potentials rather than limitations. In that context use of simulation techniques to predict soil water regimes is attractive (e.g. Bouma, 1984). However, existing simulation models that produce good results for sandy and loamy soils under field conditions cannot be used for clay soils because underlying Darcy-Richards type flow theory does not apply in soils with cracks (Klute, 1973). Many soil-physical studies have attempted to develop flow theory for swelling soils but such studies have not yet reached an operational stage for field applications (Youngs, 1983; Smiles, 1984). The same is true for studies on the effects of macropore-flow, as summarized by Beven and Germann (1982).

A different deterministic approach using both soil morphological and physical data has been developed for heavy clay soils in the Netherlands (Bouma, 1984 a, b; Wösten and Bouma, 1985). These studies emphasized specific land qualities such as soil water availability, trafficability and aeration status, in the context of studies on land evaluation. Attention in this paper will arbitrarily be focussed on measurement methods and on the feasibility of using predictive simulation models. The swell-shrink nature of clay soils requires the distinction of dynamic wetting and drying cycles, that are not only a function of environmental boundary conditions of the flow system (e.g. cli-

mate, watertable level) as is the case in non-swelling soils, but also of the changing basic hydraulic properties of the soil. Separate attention will be paid to: (i) infiltration, (ii) water storage, (iii) hydraulic conductivity in saturated and unsaturated conditions, (iv) upward fluxes from the water-table, and (v) water-table fluctuations. Simulation results of the soil-water regime will be presented for one of the soils being discussed.

PEDON DESCRIPTIONS

Studies were made in three fine-textured soils, which were described as follows:

Pedon 1

Location: Kerang, Australia.
Classification: Very fine, mixed, thermic, Entic Chromustert.
A1: 0-20cm. Very dark grayish brown (10YR3/2) clay (50%), fine subangular blocky structure, many fine grass roots with some iron staining.
AB: 20-30cm transitional horizon to
Bw1: 30-45cm. Brown (7.5YR5/5) with dark grayish brown materials in vertical zones (infilled cracks) clay (70%), fine subangular blocky structure with many fine cylindrical pores.
Bw2: 45-60cm. Brown clay, some dark grayish brown infilled worm channels, some soft carbonate concretions; many fine cylindrical pores, slickensides.
Bw3: 60cm +. Brown clay, subangular blocky structure, slickensides.

Pedon 2

Location: Narrabri, Australia.
Classification: Very fine, montmorillonitic, thermic, Typic Pellustert.
Ap: 0-15cm. Very dark gray (10YR3/1) clay (60%), weak fine subangular blocky structure; self-mulching, few carbonate concretions.
Apk: 15-25cm. Very dark gray clay; large columnar structure parting to subangular blocky peds; few carbonate concretions.
Bk1: 25-30cm. Very dark gray clay, strong parallelepipedal structure parting to medium angular blocky peds; few carbonate concretions.
Bk2: 30-80cm. Very dark gray with few fine, diffuse brown (10YR4/3) mottles; clay (60%); strong parallelepipedal structure, common slickensides and carbonate concretions.
Bk3: 80cm +. Very dark gray clay with sharp, distinct mottles, many slickensides and carbonate concretions.

Pedon 3

Location: Zaltbommel, the Netherlands.
Classification: Very fine, mixed, mesic Typic Haplaquent.
A1g: 0-8cm. Dark grayish brown (10YR3.5/2) mottled clay (55%), moderate medium compound prisms parting to strong, fine subangular blocky peds.

Bwg1: 8-25cm. Dark gray (10YR4/1.5) mottled clay.
Bwg2: 25-50cm. Dark gray mottled clay (50%) with strong, medium angular blocky peds.
2A1b: 50-64cm. Old buried surface horizon with clay texture.
2Bwg3: 64-100cm. Dark gray clay with strong, coarse, smooth prisms with shiny vertical ped faces (see Bouma et al., 1979 a).

ELEMENTS OF THE SOIL WATER REGIME

Infiltration

Infiltration theory applies to soils in which cracks have been closed by swelling (Talsma and Van der Lelie, 1976). Then, the soil acts as a relatively homogeneous porous medium (condition 3 in Fig. 1). However, such conditions are not necessarily associated with very low hydraulic conductivities.

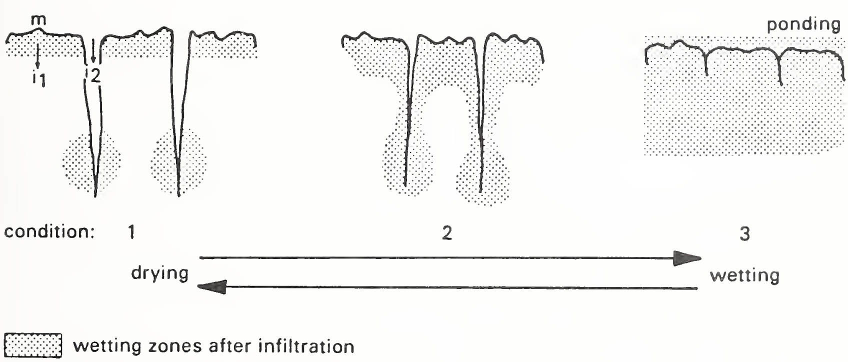

Fig. 1 Schematic diagram showing the effects of wetting and drying on cracking in clay soils.

Clay soils in the Netherlands still had final infiltration rates of 0.5 m day^{-1} even though no cracks were visible under wet conditions (Bouma et al., 1979 a). These flux densities resulted from effective crack widths, after swelling, of approximately 30 microns, as shown by staining studies (Bouma et al., 1979 b). Observed ponding of water in the field was not a result of intrinsic low infiltration rates but of compaction or puddling of the soil surface which closes the very small cracks. Besides the fully swollen condition, there are two other conditions in clay soils for which it is important to establish the nature of infiltration. The driest condition (No. 1, Fig. 1) with the cracks at maximum width usually occur at the break of season or the beginning of irrigation while condition 2 (Figs. 1 and 2) represents the situation with an actively growing crop requiring re-irrigation or rainfall to sustain growth. Both conditions are associated with bypass flow, which consists of the vertical movement of free water along macropores through unsaturated soil horizons (Bouma, 1984b). Water flows into the cracks (i_2 in Fig. 1) when the application rate of water, by rainfall or irrigation, exceeds the vertical infiltration rate into peds (i_1 in

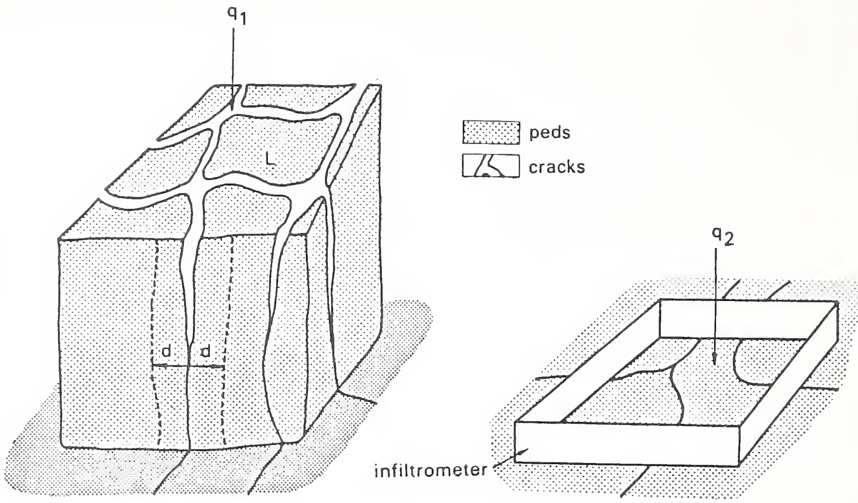

Fig. 2 Schematic representation of the measurement of infiltration patterns of water in a shallowly flooded dry clay soil (after Wösten and Bouma, 1984).

Fig. 1). Such a slow mechanism has been identified as significant to various aspects of management. Two examples are given. Kissel et al. (1974), using Houston Black clay in Texas (Udic Pellustert), measured significant leaching losses of applied fertilizers which were carried through preferential pathways by percolating rainfall, bypassing the bulk of the soil in the structural units. McIntyre et. al. (1982) found for a gypsum-treated sodic clay ponded for rice growing, that there were two wetting phases, initially a rapid movement into dry soil along planar voids and other macropores to at least 2.7 m depth, followed by a secondary slow wetting phase as water moved into intrapedal pores to gradually saturate the soil. In this case the bypass mechanism resulted in substantial losses of water by deep percolation with potentially undesirable effects on the rate of rise of groundwaters.

Bypass flow can be measured by using large undisturbed cores of surface soil with a length that is equal to rooting depth (Bouma et al., 1981). For Dutch clay soils, cylinders are used with a length and diameter of 20 cm. Cores include the soil surface with grass, which is closely cropped. The exposed cores are placed in the path of a spraying gun in the field which is commonly used for sprinking irrigation. The mass of the soil-filled cylinder is determined before and after sprinkling and the oven-dry mass is measured at the end, thus allowing calculation of physical constants such as bulk density and moisture contents. Sprinkling intensities and duration should be measured independently. The volume of water that leaves the column is measured as a function of time, thus allowing an estimate of bypass flow which can be expressed as a percentage of the applied quantity of water. Many measurements can be made in a short time and the effects of using different application regimes, initial moisture contents and different surface characteristics of the soil can be evaluated.

Results, reported by Bouma et al. (1981) and Dekker and Bouma (1984) showed that bypass flow decreases with decreasing quantity and intensity of water application. It increases at higher moisture contents of the soil, but only as long as cracks are vertically continuous. This phenomenen is due to lower vertical infiltration rates (i_1) into the peds, allowing more water to flow into the cracks. The effect of microrelief is important. Bouma et al. (1981) showed that bypass flow could be reduced by a factor of 50% when increasing the microrelief of the soil and, thereby, surface storage of water. The type of structure was important because more bypass flow occured in soils with small peds.

The dynamic character of the infiltration process is illustrated in Figure 1. The rate of closure of cracks upon wetting is a highly complex function of wetting rate and method of wetting, the chemical composition of the water, soil structure and the clay mineralogy of the soil. Repeated observations in the field are most suitable for characterizing the relative importance of the individual factors. For Dutch conditions the change from condition (1) to (3) (Fig. 1) takes several months in fall and early winter of the year. The drying cycle occurs in early spring and takes a comparable period of time. Measurements on wet samples should, therefore, under Dutch conditions only be made in the late-winter season when natural swelling has occurred. Saturation of dry soil samples in the laboratory yields unrepresentative results for wet conditions. Much more has to be learned about the dynamics of the soil system as schematically shown in Figure 1, also as a function of irrigation practices. Water infiltration in rapidly swelling soils may only be possible by using the mechanism of bypass flow, the effects of which can be manipulated by soil tillage and the water application regime.

Water storage

Bypass flow is also influenced by the vertical continuity of the cracks. In Dutch clay soils, as studied by Bouma et al., 1979a, b; cracks are vertically continuous, even in a swollen, wet soil. They connect with a permeable clay-subsoil in which tile-drains are placed. However, they will fill with water, at high rain intensities or after ponding. This condition will also occur for many clay soils when flooded (Graecen and Gardner, 1982). The resulting flow process is complicated. Water will infiltrate vertically and laterally into soil with peds between the cracks. This process may be associated with compression of air inside the peds, which in turn may result in positive pressures being registered by tensiometers. Obviously, in this case these positive pressures do not indicate saturation with water. An analysis of flow processes during ponding of water on an initially dry clay soil was made by Bouma and Wösten (1984). They carved out a cube of dry soil which was encased in gypsum. After shallow ponding of water on top of the dry soil, different flux densities were measured as indicated in Figure 2. Flux q_1 is the vertical infiltration rate into the cracks during shallow ponding of water. Flux q_2 into the underlying subsoil was measured seperately with an infiltrometer after removal of the soil-cube.

The difference between fluxes q_1 and q_2 is the rate by which water is absorbed by the soil. Absorption occurs vertically at the upper surface and laterally from the cracks into the dry soil to a distance of d cm in Fig. 2. The length

of the cracks in horizontal cross section is important in determining the total volume of water that is adsorbed laterally. Morphometric counts were made of the total length of crack walls in horizontal cross section (= L cm in Fig. 2). Then, a simulation model was used to calculate lateral infiltration. Detailed results, reported by Bouma and Wösten, (1984) showed that these calculations agreed well with the actual field monitoring data. Comparable results were obtained for the adsorption of sprinkling irrigation which was not associated with complete filling of the cracks (e.g. Hoogmoed and Bouma, 1980). These examples show that infiltration processes in dry or moist, cracked soil can be described in quantitative terms by defining several subsystems of flow, to be combined in a comprehensive model. These subsystems are defined using soil morphological methods.

HYDRAULIC CONDUCTIVITY

Measurement of hydraulic conductivity of saturated soil (K_{sat}) in clay soils requires use of large samples in which macropore-continuity patterns are representative for patterns occurring in natural soil. Many methods using large samples are available (Bouma 1983). The cube method was newly developed.

This method (Bouma and Dekker, 1981) uses a cube of soil (25 cm × 25 cm × 25 cm) which is carved out in situ and encased in gypsum on four vertical walls. If long-term experiments are planned, encasement in cement is recommended to avoid softening and leakage of the gypsum cube. First, the K_{sat} (vert) is measured by determining the flux leaving the cube while a shallow head is maintained on top. Next, the cube is turned vertically through 90°. The open surfaces are exposed. Again, a K_{sat} is measured which now represents the K_{sat} (hor) of the soil in situ (Fig. 3). The overburden potential is ignored, which may present a problem when measuring subsoil samples (Talsma and Van der Lely, 1976).

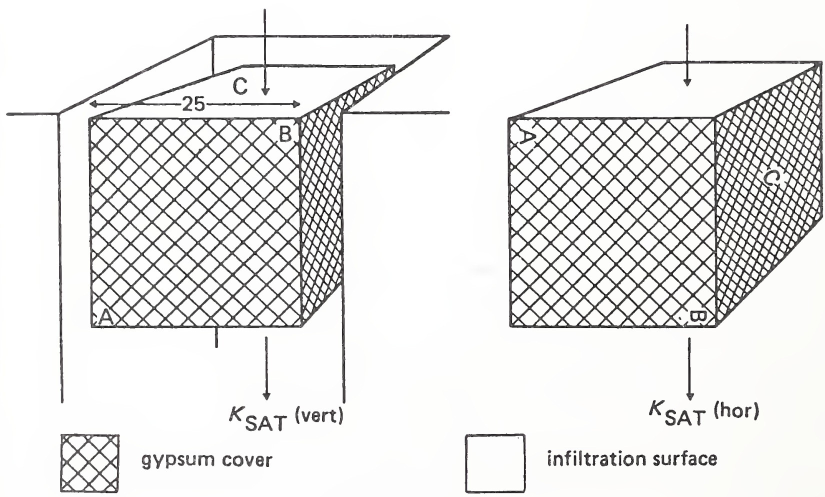

Fig. 3 The cube method for measuring K_{sat} (vert.) and K_{sat} (hor.).

To understand water regimes of clay soils, it is important to also know K_{sat}, particularly near saturation, because usually a strong drop of K occurs upon desaturation. This drop is due to emtying of the macropores (Bouma, 1982). The cube method can be extended to provide K_{unsat} data near saturation. This procedure represents a version of the crust test (Bouma et al., 1983). Two tensiometers are placed about 2 and 4 cm below the surface of infiltration, which is covered by a series of crusts, composed of mixtures of sand and quick-setting cement. Earlier, the crust test used gypsum but this may dissolve thus increasing the electrolyte content of the infiltrating water and influencing K_{unsat}, as demonstrated by Scotter (1985). Dry sand and cement are thoroughly mixed. Water is applied and a paste is formed which is applied as a 0.5 cm to 1 cm thick crust on top of the cube. The crust, which has perfect contact with the underlying soil because of the application method, hardens within 15 minutes. Light crusts (5 to 10% of cement by volume) induce pressure heads (h) near saturation and relatively high fluxes. Heavier crusts (20% cement and more) induce lower h values and fluxes. Cement can be added to existing crusts to avoid removal of crusts which could cause damage. Fluxes, when steady, are equal to K_{unsat} at the measured subcrust h value at unit hydraulic gradient. Cubes can be placed on a sandbox to create a semi-infinite porous medium. Thus, the range of fluxes can be extended to corresponding pressure heads of approximately 60 cm.

Measurements of K were made in the three soils mentioned earlier. Results are summarized in table 1. The strong drop of K upon desaturation is demonstrated for the Chromustert and the Haplaquent. Of particular interest is the effect of the salt concentration of the percolating water on the measured K_{sat} value. This effect was demonstrated for the Chromustert. Using irrigation water (EC = 150 S cm^{-1}; SAR = 2.7), yielded significantly lower K_{sat} values than when using drainage water (EC = 50 000 S cm_{-1}; SAR = 51). Slight differences in soil swelling, resulting from different salt concentration in the water, have a significant effect on the sizes of the "necks" in the flow system that govern K_{sat} (Bouma et al., 1979a). Methylene blue was added to the percolation water to stain water conducting pores. Results for the Chromustert

Table 1 Results of measurements of hydraulic conductivity in three heavy clay soils.

		K_{sat} ($cm\ day^{-1}$)				K_{unsat} ($cm\ day^{-1}$
Location	Depth (cm)	Vert. (high salt)	Vert. (low salt)	Hor. (high salt)	Hor. (low salt)	(vertical)
Kereng	10-30	30	12	24	4	2 (h = −5 cm)
Chromustert	10-30	95	43	18	4	3 (h = −6 cm)
	50-70	65	20	58	16	4 (h = −5 cm)
	50-70	18	24	72	38	6 (h = −6 cm)
Narrabri	20-45	—	0.7 (4 replicates)			
Pellustert	45-70	0.6	0.3 (4 replicates)			
Zaltbommel	30-60	5 ± 3 (no tile drainage (20 replicates)				3 (h = −5 cm) 10 replicates
Haplaquent		50 ± 15 (tile drainage) (58 replicates)				

(No. 1, Fig. 4) show that both channels (tubular soil voids) and cracks (planar voids) conduct water, whereas for the Pellustert (No. 2) only very infrequent channels do so, despite the presence of numerous planar voids. The picture for the Haplaquent (No. 3, Fig. 4) shows that planar voids conduct water. Results of this kind, taken together with other measurements can be used to predict the likely consequences of various management practices; for example, Loveday and Cooper (1984) used data on K_{sat}, exchangeable cations and water conducting pores to predict the likely outcome of tillage and ameliorative treatments on infiltration, drainage and leaching in several soils.

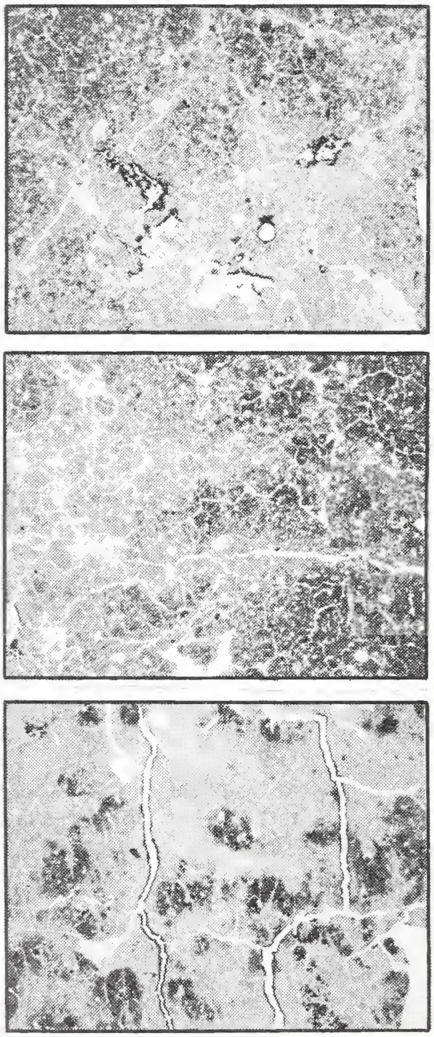

Fig. 4 Horizontal thin section images of the three clay soils showing water conducting macropores as indicated by stained walls: stained channels (c) in soil 1; no stained pores in soil 2 and stained planar voids in soil 3.

Upward fluxes

Vertical cracks may result in bypass flow. However, soil shrinkage also causes the formation of horizontal cracks which strongly impede upward flow of water in unsaturated soil (Bouma and De Laat, 1981). A method was devised to stain air-filled horizontal cracks at different moisture contents and corresponding (negative) pressure heads. A cube of soil (30 cm × 30 cm × 30 cm) is carved-out in situ (Figure 5). The cube is encased in gypsum and is turned on its side. The upper and lower surfaces are opened and two sidewalls of the turned cube are closed. Methylene blue in water is poured into the cube and will stain the air-filled cracks. The surface area of these stained cracks is counted after returning the cube to its original position.

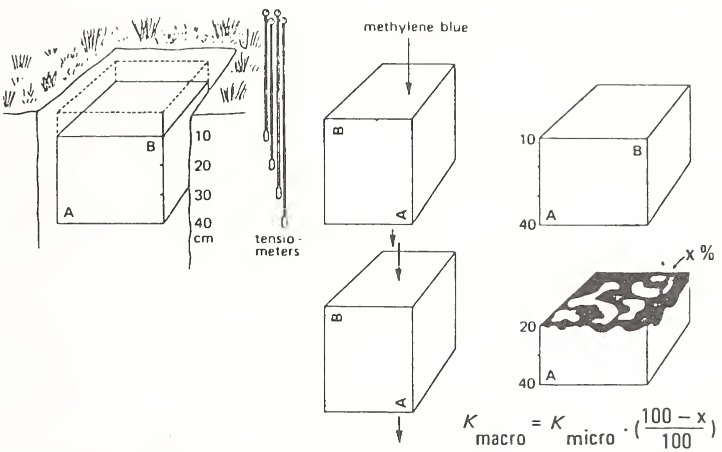

Fig. 5 A schematic representation of the method for measuring the area of air-filled horizontal cracks as a function of the pressure head. Stained planar voids occupy x% in horizontal cross section.

A separate cube is needed for each (negative) pressure head. The K-curve for the peds (curve for the Haplaquent is shown in Figure 6 as K-micro) is "reduced" for each pressure head measured in a cube.

When, for example, 50% of the horizontal cross sectional area is stained, K_{unsat} for upward flow is 50% of the K_{unsat} at the same pressure head in the peds. This reduction reflects the reduced horizontal cross sectional area that is available for upward unsaturated flow. Roots growing on the surface of peds, however, are only affected by the hydraulic properties of the soil matrix, not considering macropores.

Many irrigated clay soils have relatively shallow watertables, from which water and salts are likely to move to the surface by upward unsaturated flow. Horizontal cracks have a profound impact on the upward rate of movement, as was demonstrated by Bouma and De Laat (1981) for the Haplaquent.

Perhaps more typical of Vertisol subsoils are parallepipedal or wedge shaped structures, in which the long axes of the units, and hence of the planar voids, are at 10 to 60° from the horizontal. The influence of these voids on upward fluxes has not been thoroughly investigated. Such voids may have

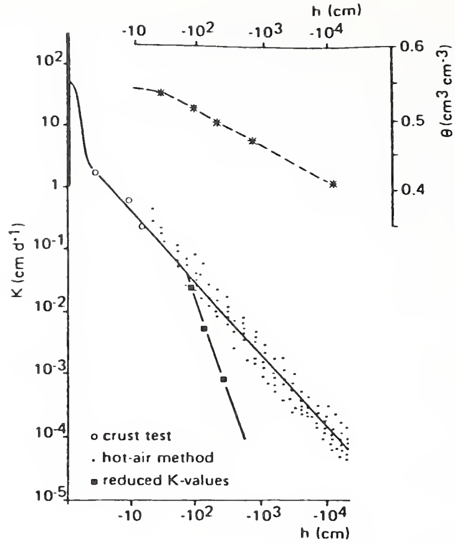

Fig. 6 K curve for a heavy clay consisting of the regular curve which defines water movement in the peds and a K_{macro} curve which is used to define upward, unsaturated flow from the water-table. Three cubes of soil were used to obtain the three reduced K values that are indicated.

been present in some of the soils used in capillary rise investigations by Talsma (1963) and McIntyre et al. (1982). In the sodic clay used by McIntyre, water was transmitted rapidly upwards to a vertical distance of about 0.30 to 0.45 m from the watertable, mainly through interconnected vughs and channels. Subsequent movement was extremely slow.

Water-table levels

The water-table is usually defined as a horizontal plane below the surface of which the water has zero pressure. Conditions in clay soils are different and monitoring data or results of simulation may appear to be erroneous when the specific character of water-flow in clay soils is not recognized. Bouma et al. (1980) showed that water moved very rapidly downward by bypass-flow along macropores towards the water-table, which, as such, is not defined for several hours after rainfall or irrigation because free water will be present in the planar voids while the surrounding soil is unsaturated (see W in Fig. 7).

Tensiometers, that intercept the planarvoids will register saturation. A special problem may occur when water-tables are measured in unlined augerholes (A in Fig. 7). When these holes end within a ped, they may partly fill with water that entered the hole through its sidewall as it flowed along a planar void (see the indicated pattern in Fig. 7). The free water level in the unlined augerhole, of course, does *not* indicate the presence of a water-table. Water table levels can be measured reliably with piezometers or tensiometers, as soon as the the free-water in the macropores has been absorbed by the

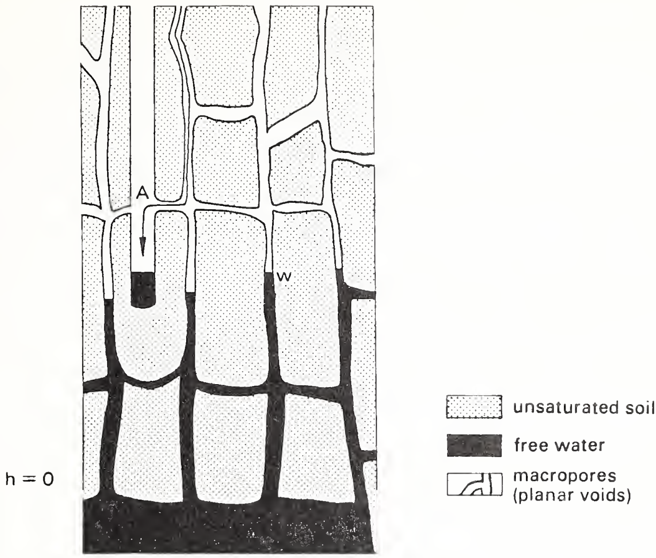

Fig. 7 Schematic diagram illustrating the undefined character of a watertable after rainfall or irrigation when free water occurs in planar voids (w) surrounded by unsaturated soil. Occurrence of free water in an unlined augerhole (A), as illustrated, does not indicate presence of a water-table.

matrix and a water table level of zero pressure has been re-established after rainfall.

Simulation

Computer simulations of the yearly soil water regime for the Haplaquent under grass vegetation were presented by Bouma and De Laat (1981) and Bouma and Wösten (1985). They included the effects of bypass flow and limited upward fluxes, as discussed above. Water extraction from the root zone was expressed by a sink-term, which defines water uptake as a function of the pressure head (Graecen and Gardner, 1982). For further details, the reader is referred to Bouma and de Laat (1981). The approach that is illustrated here for the Haplaquent only, combines soil morphological and physical techniques, emphasizing occurrence of macropore-patterns. The soil matrix is considered to be "soil between the macropores." When calculating fluxes into and through the soil matrix, swelling and shrinkage phenomena cannot be ignored, if a wide range of moisture contents is considered. Physical data by Bouma and De Laat (1981) were therefore defined in terms of the *total* soil volume, excluding the changing macropore-volume.

A comprehensive characterization of soil water regimes, as discussed, can be used to expand pedological descriptions of mottling patterns associated with soil drainage. These descriptions are hardly diagnostic since differences between chromas and values in different soils are small (Blokhuis, 1982).

DISCUSSION

The following points appear to be relevant for future studies of water regimes and associated land and water management in clay soils, such as Vertisols:

(1) Use of the bypass flow phenomenon to realize effective infiltration of water during irrigation or during natural rainfall patterns. The type of surface structure, to be manipulated by soil tillage, and the rate of application of water, its intensity and its chemical characteristics, will govern bypass flow and the rate by which macropores will close at the soil surface.

Application of a series of short, high- intensity applications of water may be most effective in inducing flow of water into soil cracks, because there will be insufficient time for closure of surface cracks by swelling.

(2) Measurement of crack-volume and rates of crack-volume decrease upon swelling. Soil structure, in terms of spacings of cracks, their width and depth is important because these characteristics determine the storage volume of water. The rate by which crack volume decreases as a function of swelling is important for management purposes.

(3) Determinations of crack continuity patterns as a function of water content is important to assess the potential for flow into the subsoil and the feasibility for tile-drainage. This aspect is also relevant for horizontal crack continuity which governs upward movement of water and salts in unsaturated soil.

Descriptive studies should be expanded to include functional staining of cracks or other functioning macropores.

(4) Measurements of the hydraulic conductivity (K_{sat}) of the saturated soil matrix, as reported in this study, demonstrate significant differences in values between Chromusterts and Pellusterts, resulting from different types of porosity as studied with micromorphological techniques. K_{sat} values at defined salt concentrations, are important reference values for clay soils. Staining studies are necessary to determine which types of macropores are active in conducting water.

(5) Further development of comprehensive simulation models for the water regime is needed to judge the relative importance of the many processes that occur during the year. Simulation may also be needed to quantify the expression of soil water regimes in soil classification systems. Current descriptive systems, are hardly diagnostic.

SUMMARY

Water regimes in heavy clay soils, such as Vertisols, are difficult to characterize because the porous medium has constantly changing dimensions due to swelling and shrinkage. Macropores, such as cracks between peds, have a strong impact on flow processes. Many standard soil physical methods do not yield satisfactory results in clay soils. Alternative methods and procedures are discussed to characterize: infiltration, water storage, hydraulic conductivity of both saturated and unsaturated soil, upward fluxes from the watertable and water-table fluctuations. A simple simulation model is discussed which combines morphological and physical data.

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Chapter 6

MANAGEMENT OF VERTISOLS IN THE HUMID TROPICS

N. Ahmad

INTRODUCTION

Most Vertisols occur naturally in sub-humid to semi-arid climates since it is in these areas of the world pedogenetical processes lead to the synthesis of smectite mineralogy as a natural product of soil formation. In more humid climates the rapid rate of leaching ensures the end product of in-situ weathering to be largely kaolinite, regardless of the basicity of the parent rock.

In the humid tropics, Vertisols develop on parent materials essentially of clay texture in which smectite minerals are already present and their occurrence in the soils are not dependent on current pedogenesis. Such materials, usually sediments, were initially deposited in marine, brackish, coastal, riverine or deltaic positions and smectite was pre-formed in an environment rich in cations. Vertisols also occur in the humid tropics on marls and some corals in which there is a high percentage of non-carbonate residues, mainly muds from the ocean floor, rich in smectite; this is inherited by the soil as the carbonate materials are dissolved in normal weathering of the calcareous materials.

Although data exists indicating the extent of occurrence of Vertisols throughout the world, no reliable estimates are yet available for those occurring in the humid tropics. However, it is believed that these Vertisols are distributed world wide. Since most of them are formed on sediments, the relief on which they occur is generally flat and due to the high rainfall and inferred poor surface drainage, the soils can be annually inundated for long periods of time.

Vertisols are well known to have specific management requirements in the sub-humid and semi-arid climates in which they occur, due to their particular tillage properties and difficulties and importance of appropriate water

management. These problems in management are intensified in a humid climate where the annual weather cycle can be manipulated only to a very limited extent. There are very serious constraints on tillage operations as the soils may be usefully tillable only for short periods each year; soil drainage is also of the greatest importance in which emphasis is placed on land layout to facilitate surface run-off.

Due to the particular environmental conditions, the actual crops which may be grown are limited and careful attention must be given to this aspect as well.

The management of Vertisols for successful permanent and stable crop production requires a full understanding of the behavior of the soils and of all other environmental factors. Considerable skill and precision in timing of field operations are required by farmers and elaborate land reclamation and water control measures are essential pre-requisites. In this Chapter, these problems are considered.

THE HUMID TROPICS AND OCCURRENCE OF VERTISOLS

It is necessary to first define what is meant by the term "**humid tropics**." There are actually very few definitions of this term; the existing ones include areas in the tropics receiving >1200 mm annual precipitation with 6 months during which evaporation is greater than precipitation, to those receiving <3,000 mm per annum with no dry months (Young, 1976). The humid tropics has also been defined as the belt between 10°N and 10°S of the Equator with uniform day length and rainfall in excess of 1,000 mm/yr, usually falling within 5 to 6 months and in storms of high intensity (Wijewardene, 1978). Ibadan in Nigeria where the International Institute for Tropical Agriculture is located to serve the humid tropics, has a climate which just meets the minimum limits outlined above. However, there are areas in the tropics which gets much higher annual rainfall and especially in the equatorial region, the amount received could exceed 3,000 mm with no month having less than the evaporative demand. If we accept the definition in Soil Taxonomy (Soil Survey Staff, 1975) for udic moisture regime, the soil in the moisture control section should not be dry in any part for as long as 90 cumulative days each year. If the precipitation exceeds evapotranspiration in all months of most years, there are occasional periods when stored moisture is used but the moisture tension rarely becomes as great as 1 bar in the soil moisture control section. This moisture regime is the perudic and the moisture balance shows a surplus for each month of the year.

In the tropics the temperature regime must also be defined and in the humid tropics which is more equatorial, this is mainly isohyperthermic in which the mean annual temperature is greater than 22°C and the summer/winter variation is less than 5°C. Therefore, in a strict sense, Vertisols in the humid tropics should be those soils which occur in udic or perudic moisture regimes with isohyperthermic temperatures. In this paper, however, the concept of the humid tropics as defined by Wijewardene (1978) is adopted.

Vertisols of the humid tropics are generally developed on pre-weathered fine-grained sediments such as alluvial deposits of riverine, estuarine, lacustrine or coastal origins of relatively recent age. Such materials are usually rich

in clay-size minerals in which pre-formed smectite is important. The sediments may not have originated from a base rich environment but if water transport is over a long period of time and especially if there is marine influence during transport, transformations could occur leading to the development of smectite-like minerals. The Amazonian sediments are good examples of this because the materials originate from the Andes and at source are rich in micas. During water transport, first fresh, then saline, the same materials when deposited on the South American coast such as in Suriname and Guyana are very fine with a high percentage of smectite (Ahmad et al., 1962; Ahmad, 1984). Soils which develop on these materials tend to be Vertisols or Entisols with vertic properties. In some places also, marly parent material in which the insoluble residues are rich in smectite could weather, leading to solution of the $CaCO_3$ and progressive accumulation of the insoluble material already rich in smectite (Ahmad et al., 1969). Normally, leaching is too exhaustive for the needed accumulation of cations required for the synthesis of smectite for in situ genesis of Vertisols as a product of weathering of basic igneous and metamorphic rocks.

Exceptionally, Vertisols in the humid tropics develop from in situ weathering of basic rocks and where they do, the length and intensity of the dry seasons lead to desiccation of the soil, accumulation of cations and consequent genesis of smectite.

As far as is known, most Vertisols of the humid tropics are developed on sediments of recent age on mostly flat topography. There are instances, though, where the sediments can be older, particularly in the case of lacustrine material, and in these instances there can be some relief in the topography. With a humid climate and essentially flat topography, these soils can remain inundated for long periods each year, coinciding with the duration of the main wet seasons. The length of time of flooding and existence of generally waterlogged conditions may be quite important in potential Vertisols to be classified as Entisols or Entisols with vertic properties. Attention is being given internationally to the classificataion of wet Vertisols (Comerma, 1985; Comerma et al., 1988).

There are large areas in the humid tropics in which the main components of Vertisol morphology are present i.e. fine texture and high content of smectite minerals. Such soils crack widely but not deeply, since there is not the opportunity for deep drying of the profile. As a result, slickensides and the associated vertic soil structure do not form to the extent needed for classification in the Vertisols. However, the features and problems in using these types of soils are the same for the more genuine Vertisols, to which they may eventually develop after reclamation and drainage.

SOME FEATURES OF THE SOIL AND LAND THAT INFLUENCE MANAGEMENT

Soil Reaction and Fertility

Many of the Vertisols and related soils of the humid tropics are classed among the acid members (Ahmad, 1982). Normally, exchangeable Al is not important in the infertility of these soils. For instance, a clay soil with pH 4.5

could be only 25 per cent saturated with Al while at this pH other tropical soils could be more than 80 percent saturated with exchangeable Al. In many of these acid members exchangeable Mg is important in comparison to Ca. It is believed that this is indicative of slow degradation of smectite in the base deficient environments with resulting release of Mg. It may also be taken as an indication of former marine influence. Further evidence of this weathering regime is the presence of a montmorillonite/kaolinite intergrade species in these soils (Ahmad and Jones, 1969; Berry-Holder, 1985). In some cases the exchangeable Mg is a contributory factor to the poor soil structure.

Available N is always deficient in these soils. Mineralization of organic N takes place very slowly since the small quantities of organic matter is extremely stable as in the case of all Vertisols. Nitrification is always a slow process as the oxidation status is hardly even sufficient for oxidation of NH^4-N. These soils also have the ability to fix large quantities of NH^4-N in both exchangeable and non-exchangeable forms (Rodriguez, 1954; Hardy and Rodriguez, 1951). Soils with such serious drainage problems could even be temporarily anaerobic, following events of heavy rainfall and this condition could further influence transformations of N.

The available P status of these soils is highly variable; this feature is related to their origin. It is low in those soils derived from brackish to fresh water sediments but not necessarily so for soils derived from marine sediments. In the Caribbean area clay soils derived from calcareous materials have very satisfactory levels of available P (Ahmad and Jones, 1967 and 1969). In management of Vertisols of the humid tropics for maximum production, it is likely that maintenance of P availability may be an important aspect.

The K status of Vertisols of the humid tropics is usually quite good if they are derived from sediments and especially if they have previous marine history (Ahmad et al., 1962). In the Caribbean area some of these soils which are derived from relatively pure calcareous materials may have low levels of K but it is not known how widespread is this situation. Particularly, the more acid and leached members have the ability to fix K chemically and this could pose a problem in the availability of this nutrient; however, evidence obtained so far indicates that the level of exchangeable K and K saturation would have to be fairly high, much higher than required for adequate plant uptake, for appreciable fixation to occur (Ahmad and Davis, 1970). In some of the soils, plants may experience difficulty in obtaining adequate supplies of K not due entirely to low levels but partly also because of an adverse balance of exchangeable Ca, Mg and K (Ahmad and Jones, 1969).

Hydrology and Drainage

Like Vertisols anywhere, those of the humid tropics have very slow internal drainage (infiltration rates of between 2.5 - 6.0 cm/24 hours) (Borden and Warkentin, 1974; Ahmad, 1983); they also have high water retention capacities with wilting percentages often in the range 25-30 percent (g/g) and field capacity, 60-80 percent water (g/g). With these characteristics plus a flat or nearly flat topography and high rainfall conditions, adequate external and internal drainage are very important aspects of management in arable cropping. Attention must be given to this problem at the time of reclamation and its solution could involve extensive and elaborate drainage installations. Since by virtue

of the climate, crop growth usually occurs in near saturated soil conditions, the influence of actual internal drainage in providing aeration can be largely ignored and the emphasis therefore has to be on the provision of adequate external drainage to get rid of most of the precipitation. As the flat topography does not naturally allow for appreciable external drainage, this has to be accomplished by different forms of land layout such as ridges (Figure 1), broad banks (Figure 2), narrow beds (Figure 3) cambered beds (Figure 4) or a combination of these (Figure 5) on which major drainage installations are superimposed. In many cases, developed areas are empoldered and external drainage is achieved by mechanical pumping.

Fig. 1: Ridges are made for the planting of single rows of crops. The size of these ridges vary with the required spacing for the particular crop. Here, sweet potato *(Ipomea batatas)* is being grown on ridges about one meter apart. The ridges are manually or mechanically made with ridging plows.

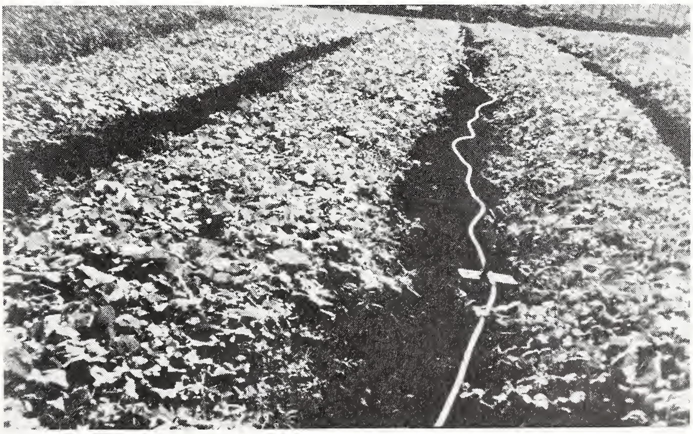

Fig. 2: Broad banks or broad ridges of about 2 m width are made for the growing of some vegetable crops where caring of the crop such as spraying, weeding, fertilizing and harvesting are done manually, the workers trafficking in the drains between the broad banks. The drains can also be used for irrigation as seen in the picture. These broad banks are usually made manually after the land has been initially plowed and harrowed.

Fig. 3A: Narrow beds, about 4 m wide are conveniently made using a tractor drawn drain-digger. The beds are used for the cultivation of a range of food and vegetable crops. Planting is done on banks made across or along the bed or on individual mounds constructed on the bed. The picture shows a recently renewed drain; note the spoil is put on one bed only. The beds were previously used for the cultivation of egg-plant *(Solanum melongena)* planted on ridges across the bed. These ridges have since subsided. After formation of the beds, the land is rotovated usually several times and further land preparation such as ridge or mound construction is done manually.

Fig. 3B: This photograph shows a cucumber crop being grown on a narrow bed in which the seeds have been planted on small mounds. These mounds would be built up as hoeing and moulding operations are carried out, to facilitate external drainage. The level of water in the drains between the beds emphasizes the difficulties of external drainage. The particular land layout poses some problems in normal caring of the crop and makes trafficking on the bed unavoidable when practices such as spraying, weeding and application of fertilizers are done.

Fig. 4: The cambered bed, about 20 m wide is used as a basic land unit for the cultivation of many crops. Its construction involves massive soil movement which is usually achieved by bulldozers. However, the land is first chisel plowed to about 50 cm depth and harrowed. Following this, the bed is shaped by bulldozer. Planting of crops is done on raised ridges on the cambered beds, either across the bed or along it. The size and spacing of the ridges are determined by the particular crops to be grown. This land layout provides good external drainage and leads to less soil erosion than other layouts but many crops perform differentially from the crest of the bed to the sides in response to soil fertility and drainage gradients.

Fig. 5: For the sugar cane crop, the individual ridges on cambered beds on which single rows of the crop are cultivated slump progressively as the crop goes through 4 or 5 ratoons before replanting. For each ratoon crop, the beds are partially reformed which essentially consists of reopening and deepending the drains between ridges.

Tillage Practices and Soil Structure

Tillage requirements and opportunities to accomplish this prior to planting a crop are extremely important aspects of management. For effective tillage, the water content of the soil is critical and if it is in a humid environment, the times and durations in the cropping year when this is reached is severely restricted. Initial effective plowing would have to be carried out towards the beginning of the dry season when the soil loosening effects would be greatest. Often, the soil does not dry out enough for plowing and primary tillage has to be done by heavy harrows or rotovators. In both cases only the dry surface soil is disturbed. Deeper tillage even when the soil is dry enough for this is of doubtful value since the effect on soil structure of wetting and drying is of much greater importance than any natural tendencies for the formation of stable aggregates or the initiation of aggregation by tillage.

Areas with marked seasonality of rainfall presents the greatest flexibility for the farmer. In such situations, advantage can be taken of the natural self mulching tendencies of the soil. Initial plowing is done at the end of the harvest and the soil then dries out for the rest of the dry season. When the rains commence, the soil clods naturally slake to the plow depth and final seed-bed preparation is fairly straightforward. As wetting continues, the soil would rapidly loose its fragmented clods and continuing water adsorption causes disruption of all soil aggregates, leading to soil sealing. By this time, the crop should already be established. Actually, the rate at which precipitation is received at this stage could be critical. About 100 mm of gentle precipitation over a period of time of about two weeks would result in satisfactory slaking of the plowed soil and another 150 mm would cause swelling and sealing. If the precipitation is received over a shorter period of time, the slaking and sealing phases would almost coincide and further land preparation may not be possible for that year.

It is believed that the deep cracks which develop during the dry season are of great importance in aeration and in provision of root space for the growing crop as the top soil becomes cohesive and the structure is disrupted (Hardy and Derraugh, 1947).

Deep tillage or sub-soiling often could have a negative effect on improvement of soil physical conditions and in promoting root growth (Ahmad and Paul, 1976). This is because the sub-soils dry out too slowly so that when this operation is carried out the soil is not dry enough to disintegrate but the tynes simply make grooves in the soft soil, smearing and even sealing the walls as they pass. Even if the sub-soil is dry enough to loosen on deep tillage, it is doubtful whether this practice would be of any benefit in the management of these soils. Swelling, aggregate disruption and sealing would occur on subsequent wetting due to natural processes.

ROLE OF CROP SELECTION

Tree Crops

Considering the problems of soil management outlined above, the range of crops which are naturally suited is severely limited. Due to their fine tex-

ture, weak soil structure especially with depth, shrink-swell properties and very poor internal drainage, they are not suited for tree crops. These crops are definitely not recommended in semi- humid and drier conditions because under these rainfall regimes the volume changes between wetting and drying are maximized. In situations where soil cracking is expressed to a maximum, the annual shearing of fine roots upon cracking imposes too much stress to tree crops. The roots of these crops are large in comparison to other crops and required larger voids for access into the soil. Such voids are usually absent except the chance soil crack which may remain partly open during the wet seasons. In general, since the sub-soil hardly ever dries out, that part of the soil remains inaccessible to roots. The tap root is unable to grow into the soil and the tree remains poorly anchored. The root system eventually ends up being severely restricted and distributed on the soil surface which makes the trees highly susceptible to moisture stress during the dry periods (Figure 6). Also, plants with such poor root systems make inefficient use of fertilizers and other soil amendments. The result is a poor orchard which is costly to maintain due to heavy weed competition mostly highly competitive grasses.

Fig. 6: Vertisols are essentially unsuitable for tree crops due to difficulties in the development of good root systems. The photograph shows the partial root system of a citrus tree. Due to poor internal drainage and little voids for root growth, roots grow literally on the soil surface and there is no tap-root development. These trees become very susceptible to moisture stress in the dry seasons and cannot exploit a large volume of soil for plant nutrients. The result is that the crop remains poor.

Among the tree crops, the palms i.e. coconut *(Cocos nucifera)* and oil palm *(Elaeis guineensis)* are the best suited on account of the vigour and great proliferation of the roots, and the fact that individual roots are never very thick. Crops which are propagated from cuttings such as cacao *(Theobroma cacao)* are particularly unsuited for these soils. The root systems of such crops are never very vigorous and they lack tap roots in any event. In Trinidad, where this crop is usually grown with overhead shade, the crop fades away after about 10-15 years when inadvertently planted on Vertisols, leaving the

overhead shade trees and any coffee which may have been inter- planted.

In Vertisol areas where the soils must be used for all crop production, orchard crops may be grown with some success if specific management practices are adopted.

Graminaceous Crops

Graminaceous crops such as cereals, sugar cane and pasture grasses are best suited for these soils. Their roots are so vigorous and extensive that the crop can better withstand damage caused by soil cracking. In the normal cycle of cultivation, the crops are usually at their maturation phase when extensive soil cracking occurs. Sugar cane seems to be the best suited of all the graminaceous crops. It can be planted when the land is still very wet — in fact in a muddy state — and it grows through the wet season, maturing during the latter parts of this season and into the dry season, when it is harvested. Since the crop naturally ratoons and it is not necessary to replant on the average more frequently than every five years, the problem of comprehensive tillage and land preparation is only in- frequently faced. The ratoon crops are only minimally tilled and this operation is carried out in times when the soil conditions are favourable.

In some places, notably in Guyana and Suriname, restoration of these soils after several years of cultivation is achieved through flood-fallowing. In this practice, after the harvest of the last sugar cane crop before replanting the area is flooded and left so for 6-9 months. During this time, the structure of the soil improves greatly due to the action of gases produced by anaerobic fermentation and the re-distribution of Fe caused by reducing soil conditions (Ahmad, 1963). After draining, land preparation and re-planting, the soil becomes rejuvenated and goes through a slow but progressive decline until it is flood- fallowed again. This management technique is now used elsewhere for crops such as banana, with beneficial results.

Other crops which can be grown in wet conditions are the cereals rice *(Oryza sativa)* and teff *(Eragrostis teff)*.

Leguminous Crops

These soils are not among the most suitable for tropical grain legume crops (i.e. cowpea (*Vigna* spp.), pigeon pea *(Cajanus cajan)*, groundnut *(Arachis hypogea)*, and beans *(Phaseolus vulgaris)* although some success is achieved by special soil management practices such as ridging. The normally high fertility enables these crops to obtain their nutrients from a limited volume of soil which is provided by ridging the most fertile and best structured top soil on which the crops are raised. Due to the extent of water-logging and poor aeration conditions, rhizobial activity can be severely restricted resulting in poor performance of the crops. Their establishment can also be hazardous since the germinating seed is much less tolerant of soil moisture fluctuations than that of cereal crops. At this critical stage, too much water-logging or temporarily dry conditions could lead to failure in establishing the crop. The moisture retention characteristics of these soils could be such that the germinating seed is sometimes unable to imbibe enough water needed for the completion of the germinating process, if soil water is limiting.

Root Crops

Many Vertisols and related clay soils in the humid tropics are used successfully for small root crops. One important tropical aroid — known as dasheen in the Caribbean and taro in the Far East (*Colocasia esculenta* var. *esculenta*) — grows equally well in inundated or aerated soil conditions and in any soil in between these extremes. In Trinidad where the crop is grown more for its leaves than the corm, cultivating it in wet soil conditions poses no problems. A related aroid — *C. esculenta* var. *antiquorum* — grows in wet soils also but requires dry soil conditions for maturation. The normal weather cycle ensures this in any event. Other tuber crops such as sweet potato (*Ipomea batatas*) and yam (*Dioscorea* spp.) are also successfully grown on ridges.

Vegetable Crops

Vegetable crops can be grown on these soils with some success; however, strict attention has to be given to land layout, land preparation and drainage and these aspects are considered later in this chapter.

Unimproved Pastures

Probably the most widespread use of Vertisols in the humid tropics is as unimproved pasture, providing seasonal grazing with low overall productivity. The native grasses which are usually aquatic or semi-aquatic are vigorous in the early part of the wet season, but as the rainy season advances and the level of inundation increases, they become reproductive and with the onset of the dry season, set seed for the next wet season. Some of them are perennial but produce at a very low level during the dry season. Improved pastures on these soils are still a problem since they require greatly improved environmental conditions before the normal pasture legumes can be introduced. Very little is yet known about adaptability and persistence of pasture legumes in these soil conditions.

SOIL MANAGEMENT UNDER DIFFERENT CROPPING SYSTEMS

Crops Tolerant Of Water-Logging

The important crops in this category are rice, teff and *Colocasia* spp. For these crops, minimum provision of drainage is needed. Tef is somewhat different from the other two since it can be sown in wet soils and in fact this is normally done; the last tillage operation in wet conditions for this crop before sowing is soil puddling as in rice culture which is a useful means of weed control. The crop, however, is fairly intolerant to poor drainage after initial establishment. The native Ethiopian practice of land drainage in the Vertisols of the wet uplands is designed to facilitate the requirements of this crop where it is the basic food crop.

For rice cultivation in which water is impounded on the land for most of the life of the crop, the topography must be essentially flat and where not naturally so, the land is contoured. The reason for flat land is to ensure ade-

quate control over the level of flooding in the entire cultivation. The main drainage requirement is to avoid excessive flooding in periods of heavy rainfall and to drain or flood the field as needed for the various cultural operations such as seeding, weeding, fertilizer application and crop maturation. Although the crop grows in standing water, the requirements for water control must be precise and require elaborate civil engineering installations to ensure this. The aroids are not very specific in their requirements except that they are really not tolerant to deep flooding and soil and land management must ensure this.

For crops which can be grown in either wholly or partly dry or water-logged conditions, such as rice, some aroids, teff, sugar cane etc., most tillage operations can be done when the soil is dry, utilizing normal tillage equipment. Final land preparation which might involve puddling and levelling is usually carried out in inundated conditions. This operation is also very effective in controlling weeds. Sowing or planting of the crop takes place in muddy conditions which are maintained until the crop is established. Under rainfed conditions, manures are added prior to the final tillage operations and fertilizers are applied just before sowing or planting. In this culture it is very important to have the final tillage operation done thoroughly, not only to prepare the soil for planting, but as an aid to weed control. If weed control is not effective at this time, it is quite difficult to control them at a later stage. The same applies to any other cultural operation including use of fertilizers. The timing of agronomic practices associated with the production of these crops is often correlated with the normal weather cycle to ensure suitable climatic conditions for crop maturation, harvesting and initial tillage.

In rice culture, split applications of fertilizers are usually made but in conditions where there is some water control i.e. the farmer must be able to get water on or off the land as needed. It is regrettable that much of the world's rice is still produced in rainfed conditions which limits fertilizer use for this important crop.

Crops Intolerant Of Water-Logging

These include the normal field crops of the tropics such as maize, grain legumes, sugar cane, oil seeds, some root crops etc. Among this group are crops with differing abilities to withstand water-logged soil conditions. Maize for instance is intolerant of water-logging while sugar cane has some tolerance. Most root crops and grain legumes are also intolerant of water-logged soils. These crops can only be grown if adequate drainage is provided. As stated earlier, the effect of internal drainage in this regard can be ignored since it is so slow that it would contribute little to the removal of water which accumulates as precipitation. Therefore, maximum provision has to be made for external drainage. Since this involves major engineering installations, this type of land is best reclaimed on a large project basis in which the necessary infra-structure for effective external drainage is provided. In practice, this involves empoldering the area to be developed with the establishment of subsidiary drainage channels and forming a network of waterways (Figure 7). In many cases essentially flat land is involved, and drainage of the developed area has to be done by pumping with enough capacity to relieve flooding over a relatively short space of time.

Fig. 7: For proper land development on Vertisols and Entisols with vertic properties in the humid tropics, elaborate drainage and irrigation systems are necessary which function independent of each other. The photograph shows the layout for sugar cane cultivation in Guyana in which up to 20 percent of the land surface is taken up with drainage or irrigation channels of all categories. Clearly, the establishment of this particular land layout is costly, require specialised engineering skills and can only be undertaken on a large project basis.

In some circumstances, when low lying and flat Vertisols areas are being reclaimed, a system of water control is constructed, not just facilities for drainage. This enables all-year farming and optimum utilization of the land which is important since the costs involved in successful reclamation are quite high. For instance, in Guyana, in order to provide a satisfactory system for effective water management for sugar cane cultivation, about 20 percent of the land surface is occupied by water courses of all categories and the installation costs could exceed $1000 (US) per hectare. Maintenance costs are also high due to the ease with which these soils can slump on edges of canals and other water courses.

Assuming a satisfactory overall system of water control, the next stage is the layout of the land for cropping, bearing in mind that the most important aspect of drainage is external drainage. Because of this, crops are never planted on flat terrain. The land has to be laid in beds and drains or ridges, the actual width of which depends upon the type of crop and the degree of mechanization. If machinery is used for tillage such as in sugar cane or maize cultivation, the minimum width of the beds is critical and is determined by the minimum width of land for a tractor and implements to turn around. The cambered bed system of field layout has traditionally been used to provide in-field drainage. It was originally used in sugar cane cultivation but has since been adapted as a means of providing external drainage for the cultivation of other crops. The cambered bed (Figure 4) is basically an elevated bed made

by piling up the soil from the sides towards the crest of the bed which was traditionally done by hand but now with a bulldozer. The beds vary in width from 3 to 20 m (Gumbs, 1982). In cross- section the bed slopes on both sides of a center line to drains which extend along the length of the bed and which are graded to discharge the water into a collector drain. In some cases the length of the cambered bed is intercepted by one or more connector drains which run at right angles to the parallel field drains between the cambered beds. The connector drains aid in the removal of water which may otherwise collect in the drains between the cambered beds due to difficulty in maintaining a uniform grade over very long lengths.

The crest of the cambered beds may be 0.5 to 1.0 m above the bottom of the drain when newly formed and the drain which is trapezoidal in cross section may be 0.5 to 1 m wide at the top. The side slopes of the drain are normally steep in clay soils but these decrease with gradual silting of the drains. When the cambered beds are established they are not lost by future tillage. Tillage to a constant depth below the cambered surface ensures that the top of the undisturbed subsoil also slopes towards the inter-bed drains and encourages the movement of water to the drains. After tillage, the drains are reformed to prevent water remaining for long periods; this can result in inefficiency in the drainage system which can lead to water- logging at the drain edges.

The differential fertility across the bed caused by the exposure of poorer subsoil materials at the drain edges and the accumulation of top soil at the bed centers also contribute to the better growth at the crest of the beds. The resulting differential growth across the bed is not as marked in sugarcane as in crops more sensitive to water- logging. In order to further improve on surface drainage, farmers may cultivate their crops on ridges either along the length of the cambered beds or across the camber. This further elevates the surface of the soil and provides a deeper, better-drained medium in which to establish the crop. This secondary land layout e.g. ridges on cambered beds, is usually made by manual labor.

In situations in which the heavy machinery needed to construct cambered beds is not available, broad, flat beds — up to 10 m wide — with box drains (square or rectangular in cross section) are sometimes used. Unlike the cambered bed system, the entire flat bed could become inundated as soon as the drain overflows and therefore the drain size and bed width have to be adequately designed to avoid this problem.

In addition to forming ridges and furrows on a raised or cambered bed (Figure 5), these ridges are sometimes used on flat land to facilitate external drainage (Figure 1). Ridges may be made to accommodate from 1 to 3 rows of crops (Figure 2), depending on the spacing and need for water control. The current tendency is to cultivate sugar cane on ridges rather than on cambered beds as this layout is simpler for complete mechanization of production. Before constructing ridges in relatively flat areas, the land is graded in one direction or in two directions at right angles to each other, and tilled before forming the ridges and furrows. The graded field with the furrows then discharge the drainage water into a main drain at one end of the field. Due to the continuously wet conditions and the instability of the soils, a good amount of soil from the ridges is eroded away; this is a more serious problem in this layout than in the cambered bed system. The ridges and furrows have to be reformed for

every crop and there is often the need to reform the ridges even during the growth of the crop to allow for drainage.

Other aspects of management such as fertilizer use and weed control are severely constrained by the behavior of these soils. Applications of fertilizer generally have to be made during tillage and land layout to allow for mechanical incorporation into the soil since movement in solution if surface applied would take place very slowly. Nitrogen can be top dressed or applied as foliar spray if the leaves of the crops are not sensitive to damage. Both sugar cane and rice can tolerate fairly high concentrations of urea in the form of foliar sprays. In large cultivations, aerial application of solids is commonly made. During the growth of the crop it is often inconvenient, if not impractical, to apply fertilizer manually due to wet cohesive soil conditions.

There is very little information on the efficiency of N fertilizers on Vertisols in the humid tropics. However, it is expected that losses could be great due to anaerobic soil conditions, volatilization or washing of the fertilizer from the soil surface. In soils formed on calcareous materials where the pH of the resulting soils is high, losses of NH_3-N by volatilization may be particularly important (Medford, 1963). Although many of the Vertisols in the humid tropics are acid, they hardly, if ever, respond to application of ground limestone.

Control of weeds by hand weeding is rather difficult due to the cohesive soil when wet and hard soil when dry; weed control is based usually on good initial land preparation in which all existing weeds are killed. Pre- emergence treatments are also sometimes practical. Early and good crop establishment is of importance so that the crop can compete favorably with weeds and weedicides may be used in the early stages of crop growth.

Other forms of soil drainage for Vertisols are in experimental stages only. In India, experiments are being conducted on the efficiency of tile drainage, with some success so far (Holsambre et al., 1982). It is appreciated that this is costly but it permits tillage operations to be conducted at any time during the year. In Belize mole drainage is successfully used in association with cambered beds by some farmers, the moles running across the camber. This combination provides adequate drainage for maize, beans and other field crops (Ahmad, 1984). Encouraging results have also been obtained in Guyana where mole drainage is being used experimentally for sugar cane cultivation. The moles are made after the land has been graded to a pre- determined slope. The combination of land grading and mole drainage is apparently satisfactory in providing adequate drainage.

Tree Crops

As stated earlier, Vertisols are not ideal for tree crop cultivation but in many instances it may be necessary to cultivate these crops for social and economic reasons. The only feasible layout is highly cambered beds on which a single row of trees is planted at the crest of the bed. This arrangement provides the maximum drainage possible. Obviously, the drains between the beds discharge into bigger drains at right angles to these and they in turn discharge into the main drainage system.

In these soils, special consideration should be given in preparing the planting hole for tree crops. A large hole should be excavated and filled with

another more friable soil mixed with compost and fertilizers — especially P, to give the young plants a good start. If this practice is not followed growth would be slow and the orchard would never produce at a high level. In the case of citrus, the root systems become superficial (Figure 6) with no development of tap root and the trees suffer from moisture stress in the dry seasons.

Perennial leguminous cover crops as *Pueraria phaseoloides* are particularly advantageous in preventing excessive soil desiccation and cracking in the dry periods and by providing N. Because surface applied fertilizers move slowly into these soils, response to fertilizer application may not meet expectations. Grass weeds are particularly prolific in these wet clay soils. Mechanical weed control using a brush-cutter is more economical than the use of chemicals and where possible, this method is used.

Intensive Vegetable Production

Vertisols of the humid tropics are also used for intensive vegetable production (Figures 2 and 3). The land layout for these crops must make maximum provision for surface drainage due to their intolerance to waterlogged soil. The land layout usually consists of narrow ridges on which single rows of crops are grown (Figure 1) or broad ridges or banks (Figure 2) on which up to two rows of crops are cultivated. This land layout can be superimposed on a wide cambered bed in which the units can be aligned either along or across the camber. Narrow (4 m wide) beds with box drains (Figures 3 and 3a) are gaining in popularity since the drains are easily made with a tractor drawn mechanical drain-digger. The beds are usually flat and the drains can either be manually or mechanically dug.

Tillage is almost entirely shallow and done by rotovator after bed formation because deeper tillage is generally not possible due to wet soil conditions. For crops normally planted in rows, ridges are made across these narrow beds by heaping up the shallow depth of tilled soil. This is usually a manual operation. For other crops particularly cucurbits and aroids, planting is done on the flat bed with some manure being placed into the planting hole to aid early root development. The main fertilizer application is made at the time of land preparation. Although the efficiency of use may be poor, the crops can be side-dressed by surface application or in some cases, they are sprayed periodically with nutrient solution. Weed control is achieved firstly by thorough land preparation and use of pre-emergence chemicals, and by the use of chemicals during crop growth where possible.

EROSION CONTROL AND ENGINEERING ASPECTS

Where clay soils develop on recent alluvial deposits the topography is essentially flat and surface erosion is not a problem except where some relief is imposed, as in land grading and to a lesser extent from cambered beds. In areas with more relief, all forms of erosion are a serious problem in management. This is well exemplified by experience in Barbados, where, during the mid-1970's it was possible to burn the sugar cane crop prior to harvest as is normally done elsewhere. The fire destroyed the natural mulch formed by the

trash which had been a feature of sugar cane cultivation on this island for centuries. Following burning and harvest of the crop, the soil remained exposed for several months until the new crop can offer protection. During this period the soil loss was very obvious. The average decrease in yield was estimated at 4 tons per hectare during the period when burning was allowed, and this was enough to convince the authorities that the practice should be abandoned only after a few years. There were, of course, other effects of burning which contributed to the yield decrease.

Slumping and mass movement are very important aspects of soil erosion on clay soils where there is sufficient relief. This is a serious problem in Trinidad and in other tropical areas and leads to dislocations in agriculture and expensive maintenance of highways and buildings and agriculture. The problem is aggravated by cracking of the soil which allows easy access of water into the subsoil in the wet seasons. This form of erosion is also aided by the occurrence of natural shear planes or slip faces in the substratum. The water eventually finds its way between these faces and forms a lubricant on which the material above may slip. In management of clay soils prone to land-slipping, excessive desiccation should be avoided, so that cracks will not develop to a maximum extent in the dry seasons; additionally, disposal of waste water from houses, dairy pens, road-ways, on-site sewage disposal etc. should be well planned and executed. In reclaiming areas subject to mass movement this problem should be recognized and the hydrological conditions of the area should not be disturbed in the process. Failure to do this could lead to catastrophic consequences on land that has been reclaimed. Agriculture should also be very intensive including irrigation to avoid extreme variation of soil moisture which is naturally characteristic of these soils.

Another form of erosion which is serious on clay soils is gullying on banks of rivers and waterways. Cracking of the soil on the banks occurs during the dry season and with the onset of rains they may collapse, and the development of gulleys can result. If this problem is recognized at the time of reclamation, the natural vegetation can be left along the river banks for protection. Erosion also occurs along irrigation canals, leading to expensive maintenance. The only practical way of dealing with this problem is to keep canals filled with water to avoid drying out of the banks and to allow growth of vegetation that will not hinder the flow of water. Once extensive cracking develops on the banks of irrigation channels, the loss of water through these cracks would also be a problem and could lead to inefficient water use.

Collapse of soil along drainage courses leads to very rapid deterioration of these installations and they accordingly require constant maintenance. High shrink-swell properties of these soils also make maintenance of farm roads, farm buildings, surface utilities and fences very serious problem which demand expert engineering inputs and significant capital and labor imputs.

SUMMARY

The features and problems of managing Vertisols and related soils with vertic properties in the humid tropics are discussed. Vertisols in this climatic zone are mostly formed on sediments of recent age and they usually occur on flat land or land with little relief on which external drainage is poor. The soils

also have very slow internal drainage and difficult tillage properties. Therefore, soil drainage and adequate land preparation are very important management problems.

Soil drainage is achieved in arable cropping by a variety of land layouts to facilitate external drainage such as ridges and furrows, broad banks and cambered beds and combinations of these. Tile and mole drainage can also be associated where economic considerations would allow. Tillage is confined to rotovating in the wetter areas where the deeper soil dries out too slowly. In areas of more seasonally distributed rainfall initial ploughing can best be done immediately following crop harvest and before the soil gets too hard. Final land preparation can be completed just prior to planting. The nature of the onset of the rains can be very important in soil sealing, final land preparation and crop establishment.

Management of nitrogen availability is the main aspect of soil fertility needs. In particular soils, P availability can also be of great importance and less frequently, K. Al- though acid Vertisols are common in the humid tropics, use of lime is usually not beneficial in crop production.

In the humid tropics, Vertisols are used for a wide range of crops with appropriate management. Rice and other crops tolerant of inundated conditions are easily produced with adequate water control. Other cereals, sugar cane, root crops and even some grain legumes and vegetables are produced with particular land formation to aid external drainage. Vertisols are unsuitable for tree crops in this climate, with palms being better suited. For these crops, highly cambered beds are used, but even so, the root systems eventually become quite superficial, exposing the crop to severe water stress in dry seasons and root damage. Many Vertisols in the humid tropics are in unimproved pasture, the increase in productivity of which requires research inputs.

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Chapter 7

MANAGING WET VERTISOLS IN RICE-BASED CROPPING SYSTEMS

S.K. De Datta, M.E. Raymundo, and D.J. Greenland

INTRODUCTION

Vertisols are inherently productive soils, with an area estimated at 310 million ha (IBSRAM, 1985), including some Vertic subgroups of other soil orders. The level to undulating topographic positions, clayey texture and expanding clay mineralogy favor water influx and retention which are essential in wetland rice production. In tropical areas only one rice crop has traditionally been grown annually in these soils. Crop intensification has now become possible through the introduction of modern, nonphotoperiodic varieties, supplementary irrigation and adjustment in cropping systems according to the rainfall distribution patterns. Management issues involved in wet Vertisols are: a) regeneration of structure to allow establishment of upland crops after puddling for rice; b) predicting or anticipating the need for fertilizer nutrients other than nitrogen; and c) the amelioration of micronutrient deficiency or toxicity.

Wet Vertisols, as referred to in this paper, are Vertisols that may or may not have been naturally flooded but have developed wet or aquic characteristics when used in flooded rice production. Although a tendency to salinization and difficult workability have limited their development (Moormann and van Breemen, 1978), they are quite widely used in growing rice; many people depend on them for livelihood.

OVERVIEW OF WET VERTISOLS

Many pedologists (Comerma, 1985; Comerma, et al., 1988) felt the need to restore the suborder Aquert, which was defined in the 7th approximation

(Soil Survey Staff, 1960) but later deleted in Soil Taxonomy (Soil Survey Staff, 1975). The aquic characteristics are presently recognized at the subgroup level under the *Chrom*-great group but not under the *Pell*- great group of Vertisols. Our paper focuses primarily on wet Pelluderts and Pellusterts. Greater details are presented elsewhere in this publication (Comerma et al., 1988).

Occurrence of Wet Vertisols

Soil surveys used to estimate the extent of Vertisols (IBSRAM, 1985) are mostly very large in scale (1:100,000 or larger). Vertisols used in lowland rice production have been estimated at 92,000 ha in the United States, 350,000 ha in Indonesia, and 547,000 ha in the Philippines (IRRI, 1978). Smaller areas have been reported in India, Thailand, Malaysia, Pakistan, Egypt, and other Near East countries.

With full irrigation, rice can grow on wet Vertisols under very dry climatic conditions where temperature and solar energy are favorable for year-round crop production. In Uderts and Usterts where irrigation water is limited, upland crops are often planted in rice-based cropping systems to maximize land use. The possibility of lowland rice production with no irrigation is nil in areas with wet winters and dry summers (Mediterranean climate), in arid, semi-desert areas, and in climatic environments where the suborders Xererts and Torrerts occur.

Uderts are Vertisols in which cracks remain open for less than 90 consecutive days. One or more lowland rice crops can be satisfactorily grown each year with minimum irrigation if temperatures are suitable (iso- and noniso-classes of the thermic and hyperthermic temperature regimes).

Usterts are Vertisols in dry areas where cracks remain open for more than 90 consecutive days in most years. The subgroup Typic has cracks open for more than 150 consecutive days; Udorthentic indicates less than 150 but more than 90 consecutive days of open cracks. A mean annual soil temperature of less than 15°C may be a constraint to more than one cropping in the Usterts of the Udic subgroups. More than one crop per year is more probable in the Udorthentic than in the Typic subgroup of Usterts under limited irrigation.

Potential Cropping Systems in Wet Vertisols

Uderts

Lowland rice is more commonly grown on Uderts than on Usterts because of the longer period of availability of water in Uderts. Upland crops may be grown following rice in periods of lower rainfall, or after cessation of rainfall, with water stored in the profile.

The success of a cropping pattern depends on microclimatic differences, topographic position, soil properties, and whether supplementary irrigation is available. Potentially available irrigation water can be reflected in the taxon. Longer wet seasons in the Uderts not only preempt the short-duration water constraints but also indicate longer-duration or intermittent water recharge in small communal irrigation systems (Fig. 1). Planting two lowland rice crops

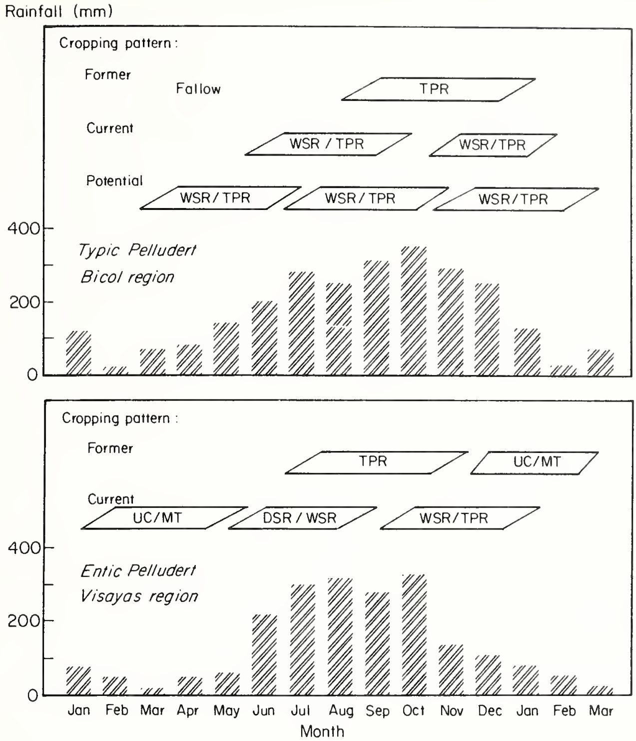

Fig. 1. Cropping systems in Typic and Entic Pelluderts in the Philippines under rainfed conditions. TPR = transplanted rice, WSR = wet seeded rice, UC = upland crop, MT = minimum tillage, DSR = dry seeded rice.

per year even without supplementary irrigation is feasible in Uderts where only one dry period occurs. An available source of supplementary irrigation serves as insurance during aberrant dry periods.

An upland crop is seldom established in wet Uderts subject to frequent flooding. On the other hand, upland crops are normally grown after two rice crops in Uderts that approach Usterts. Abrupt onsets of seasons are not normal to Uderts (Oldeman, 1984).

By virtue of topographic position, wet Vertisols are generally associated with shallow water tables, whether perched or groundwater. Operating pump irrigation is thus normally cheaper in Uderts than in Usterts. Phreatic water from the uplands associated with Uderts may also contribute to irrigation.

Usterts

In Usterts, particularly in the Typic subgroups, water impounding structures are essential to maximize cropping intensity with supplementary irrigation. Aquifers often dry up, and the probability of a successful prewet season seeding of rice using supplementary irrigation is low.

Rainfall distribution during the onset of wet season and/or dry season determines whether an upland crop should be planted before or after lowland rice (Morris and Zandstra, 1978). An abrupt onset of heavy monsoonal rains at the start of wet season limits the success of upland crops before rice, as poor drainage results in flooded soils.

Dry-seeded rice may be grown as an early crop in Usterts with a gradual onset of wet season. In the Udorthentic subgroup of Usterts, a second rice crop is highly feasible with supplementary irrigation late in the growing period (Fig. 2). Irrigation is definitely required during the critical growth stages in the Typic subgroup.

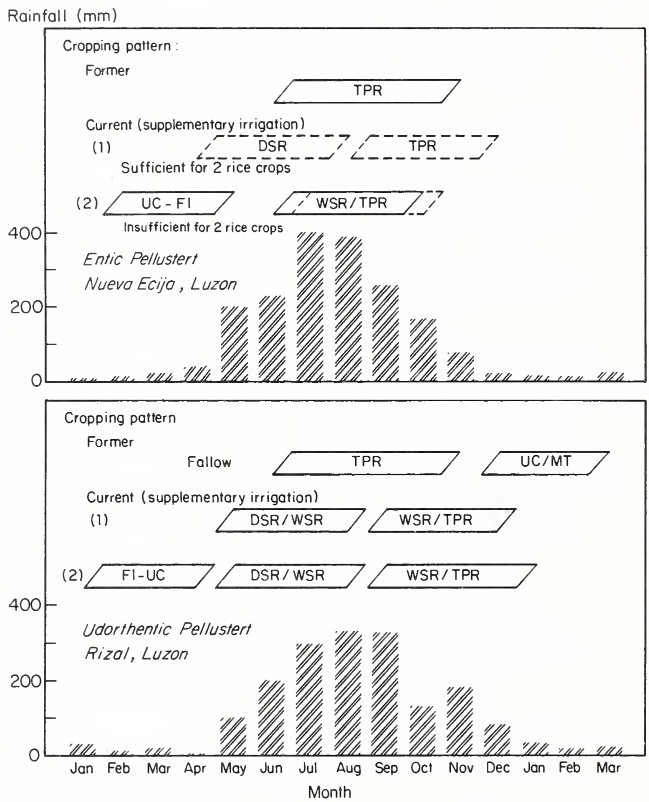

Fig. 2. Cropping systems in the Typic and Udorthentic Pellusterts in the Philippines. Fl = flush irrigation.

With a gradual tapering off of rain in the late rainy season, an upland crop under minimum tillage requires less supplementary irrigation. However, the soil still requires supplementary irrigation in amounts less than that required by a lowland rice crop.

Usterts require comparatively more water than non-Vertic soils in an Ustic moisture regime to enable regeneration of the soil structure essential to satisfactory yields of upland crops. Crop intensification is limited to rice under

a fully irrigated system. This practice is composed primarily of two rice crops per year.

The long maturity and photoperiod sensitivity of most older rice varieties limited rice production in the past to one crop even under Udic moisture regimes. The introduction of nonphotoperiod sensitive, short-maturing modern rice varieties has helped intensify production. The water retention capacity and slow internal drainage of Vertisols and Vertic subgroups under Udic moisture regimes sustain more than one rice crop per year.

Topographic position

Topographic position affects the success of a cropping pattern within similar rainfall regimes, particularly in Udorthentic Usterts. In some Usterts, the groundwater table is not only shallow — so that pump irrigation in low topographic positions is simple — but phreatic water from surrounding higher ground also reduces the period of water constraint in the early dry season.

On generally level physiography associated with Vertisols, crops on slightly higher microtopography may suffer from moisture stress 2 or more weeks earlier than those in lower topographic positions. These depressions are often old cut-off meanders, areas of old backswamps behind river levees, and beaches formed during the more recent geologic past. Water stress is also observed later in Vertisols on gentle footslopes in higher topographic positions immediately adjacent to steep backslopes of intermediate uplands, from where phreatic water recharge occurs. The same recharge processes take place in the Uderts, but the effects are not as obvious except when abnormally dry periods occur during the wet season.

MANAGEMENT ISSUES IN WET VERTISOLS

Physical, chemical, and mineralogical properties of Vertisols are all sources of management concerns in rice-based cropping systems (De Datta, 1982). The clayey texture, generally basic or near neutral pH, smectite mineralogy, and nutrient availability in the soil affect soil management in lowland rice production.

Physical Properties and Management

The high clay contents and swelling characteristics of the Vertisols make them difficult to manage. The soil frequently dries to a massive, cloddy structure that is difficult to till.

The large clods may also break down to a favorable structure on wetting (Smith et al., 1984), depending on their size and the degree to which they have dried. Most water enters the profile on first wetting through the major cracks, which are often deep enough to enable wetting and swelling to start in the subsoil. When the soil is wet, swelling closes the cracks, but they may remain slightly open as the major conduits through which water transmission occurs until the natural or perched water table is established in or above the profile.

In dry, cloddy conditions, cultivation in Vertisols is almost impossible without powerful machinery. But when the soil is softened by flooding and "land soaking" for several weeks, wet plowing with a water buffalo or small tractor becomes possible. Harrowing to puddle the soil and to destroy residual cracks or weeds is easy. Rice can subsequently be transplanted and irrigation water fully retained throughout the crop period.

The soil profile is usually saturated after the rice crop. It normally contains sufficient water for a short-term upland crop. In self-mulching Vertisols, the seeds may be broadcast by hand. Sufficient germination may be obtained for a reasonable yield if heavy rains do not flood the soil. If the soil dries slowly to a cloddy condition, a minimal tillage system and seed burial are essential.

It is debatable whether the lack of percolation in flooded Vertisols results in the accumulation of toxic byproducts of anaerobic decomposition. This accumulation is claimed by some workers to cause grain yield decline in prolonged intensive lowland rice production systems in the tropics (Si-Tu Soong and Zhang Wei, 1985; Greenland, 1985a).

Trials of the International Network on Soil Fertility and Fertilizer Evaluation for Rice at different sites and on different soils in the Philippines found different yields at similar N fertilizer application rates. Yields obtained from Vertisols were not significantly better than those from other great groups (Table 1), although experiments (Ho, 1985) have shown Vertisols to be the most productive rice soils in Sri Lanka (Fig. 3).

Table 1. Mean lowland rice yields (t/ha) at different N levels irrespective of N source at various INSFFER sites representing 4 soil orders in the Philippines.

Nitrogen (kg/ha)	Vertic Tropaquepts	Andaqueptic (Vertic) Haplaquolls	Vertisols[a]	Fluvaquentic Mollisols[b]	Aquic Troporthents	Non-Vertic Tropaquepts[c]
0 (check)	3.1	3.0	3.3	3.0	3.4	4.3
29	3.5	3.8	4.2	4.1	5.0	5.2
58	4.0	4.4	4.7	5.0	5.1	5.4
87	4.1	4.4	4.9	5.2	5.4	6.3
116	4.4	4.7	—	5.3	—	5.4

[a]Entic Chromusterts, Entic Pelluderts, and Udorthentic Pellusterts.

[b]Fluvaquentic subgroups of Haplustolls and Hapludolls.

[c]Aeric and Typic subgroups of Tropaquepts.

Chemical Properties and Management

Wet Vertisols generally have near neutral to acid pH, high base saturation, and exchangeable cations dominated by Ca^{++}, but low Ca/Mg ratio. They have moderately high cation exchange capacity (more than 30 meq/100 g soils) due to high content of 2:1 clay minerals, most of which are smectites but with minor kaolinite or halloysite. Most Vertisols have relatively small amounts of vermiculite (Dixon, 1982; IRRI, 1985), although some Vertisols in the Philippines have small to moderate vermiculite. Nitrogen contents are moderate to low; available P and exchangeable K are mostly moderate to high (Table 2).

Long-term experiments in the Philippines and Indonesia have evaluated intensive cropping on Vertisols for more than 12 years (De Datta and Gomez,

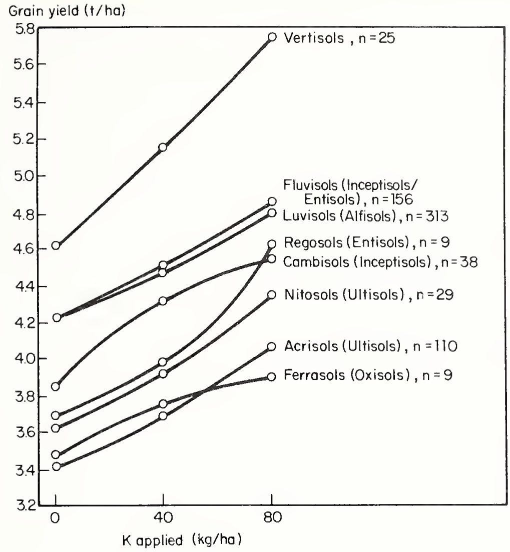

Fig. 3. Yield response of rice to K on various soil groups of Sri Lanka (Ho, 1985).

1982; Flinn and De Datta, 1984; Fagi and Partohardjono, 1982). Responses to N are high, but yield responses to N without P and K decline (Fig. 4, 5). They decline more drastically in the first three croppings in the dry season than in the wet season at the three sites. When P and K were applied together with N, yields were maintained or increased (De Datta, 1985; Greenland, 1985b). In Indonesia, yields were similarly maintained at about 5 t/ha with NPK (Fagi and Partohardjono, 1982).

Response to P

The three Vertisol sites in the Philippines showed response to P, but trends and magnitude varied among sites. Yield increases due to P (NP treatment - N treatment) were not significant in the first two dry season croppings on a fine, montmorillonitic isohyperthermic family of the Entic Pellusterts in Nueva Ecija. Yields increased at more consistent levels in the next 10 croppings. Higher yield increases were observed with only one aberrant crop in the last six croppings (Fig. 4, 5).

Of the 18 dry season croppings in Bicol on a very fine, mixed, isohyperthermic family of the Typic Pelluderts, 11 croppings showed considerable yield increases due to P application. On a fine, mixed isohyperthermic family of the Entic Pelluderts in the Visayas, P application increased yield in the last six dry season croppings.

Of 13 dry season croppings, higher rice yields were obtained in 5 croppings in Nueva Ecija, in 7 croppings in Bicol, and only 1 out of the 8 croppings in the Visayas (De Datta and Gomez, 1982). For the same duration, significantly higher yields of N+P over N alone during the wet season were obtained in two, two, and three croppings, respectively for the sites.

Table 2. Weighted averages of some chemical properties at 0-30 cm and 30-100 cm depth of 5 wet Vertisol pedons in the Philippines.

Great group	Pellusterts		Pelluderts		Chromustert
Subgroup	Udorthentic	Entic	Entic	Typic	Entic
Site	Teresa	MRRTC	Iloilo	Pili	Mangaldan
Properties			*0-30 cm depth*		
pH (H_20)	7.2	6.4	7.4	5.9	7.1
Organic C (%)	1.1	1.6	1.7	1.8	1.2
CEC (meq/100 g)	38	32	56	32	48
Exchangeable Cations (meq/100 g)					
Ca	29	22	41	20	39
Mg	9	11	16	9	10
Na	0.7	0.5	0.9	1.2	0.6
K	0.4	0.3	0.9	0.2	0.6
Ca/Mg	3.1	1.9	2.5	1.6	3.9
Available P					
(ppm Bray)	10	11	22	12	59
(Olsen)	1.2	3.1	1.8	1.7	9.1
			30-100 cm depth		
pH (H_20)	7.2	7.4	7.6	6.8	7.6
Organic C (%)	0.2	0.4	0.5	0.4	0.7
CEC (meq/100 g)	52	44	59	43	53
Exchangeable Cations (meq/100 g)					
Ca	36	24	35	28	52
Mg	15	20	21	13	10
Na	0.4	0.7	0.8	1.5	0.6
K	0.4	0.5	0.8	0.1	0.6
Ca/Mg	2.4	1.2	1.7	1.5	5.2
Available P					
(ppm Bray)	22	15	78	16	59
(Olsen)	nil	1.1	2.4	0.7	1.9

Response to K

In dry season croppings, yield response to K (NPK - NP) increased with time in Nueva Ecija and decreased with time in Bicol (Fig. 4, 5). Yield increases due to K were not observed in the Visayas. The response to K during the wet season was similar to the response during the dry season at all sites. The magnitude of K response was lower during the wet than during the dry season. Favorable effects of N on yield in the presence of K coincided with those of P.

De Datta and Gomez (1982) reported that P application tended to increase yield response to applied K. Conversely, K application increased the response to applied P at the three wet Vertisol sites.

Responses to other nutrients

Prolonged flooding is known to induce Zn deficiencies above pH 6.8 (De Datta, 1981; Ponnamperuma, 1972). Remedial measures normally practiced

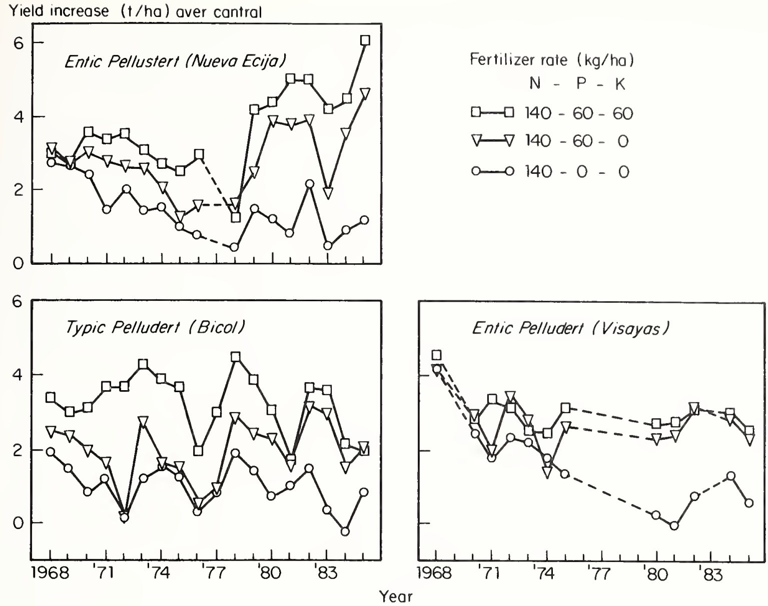

Fig. 4. Yield increases over check plots by adding N, N+P, and N+P+K in 3 long-term fertility experiments on Vertisols, 1968-1985 dry seasons (from updated IRRI data).

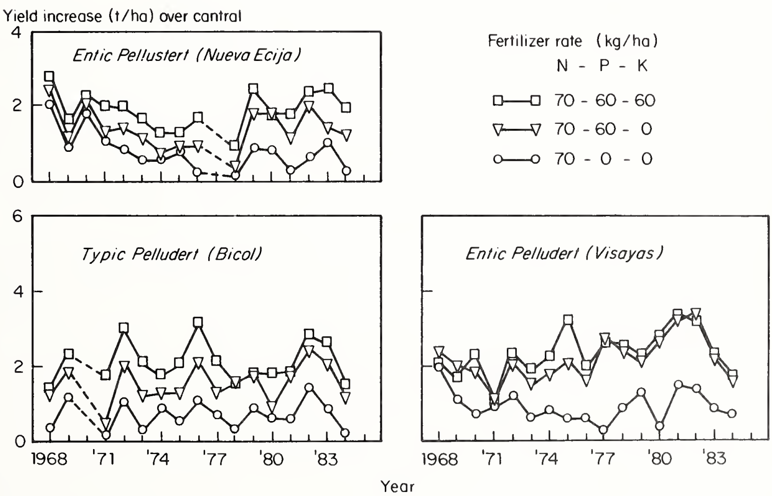

Fig. 5. Yield increases over check plots by adding N, N+P, N+P+K in 3 long-term fertility experiments on Vertisols, 1968-1984 wet seasons (from updated IRRI data).

are Zn application, dipping seedling roots in a ZnO suspension, and drying the soil thoroughly with a cultivated fallow in dry season. The dry season cultivated fallow is suspected to be effective only for the succeeding crop. Farmers experience the need for Zn treatment in the second crop after the fallow.

A high Mg^{++} level in the soil is suspected to aggravate Zn deficiency such that an exchangeable Ca^{++}/exchangeable Mg^{++} ratio of two or less at near neutral pH is considered a probable indicator of the need for Zn application. Data in Table 2 indicate that low Ca/Mg ratios may be common in wet Vertisols.

Sulfur deficiency is suspected in wet Vertisols. Sulfur sufficiency, whether associated with S-rich fumes or with the Andic properties found in wet Vertisols near volcanoes, still needs to be verified. Boron toxicity was observed in the Vertic soils at IRRI, but it is mainly attributed to the high B content of the irrigation water from deep wells.

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Chapter 8

MANAGEMENT OF VERTISOLS OF TEMPERATE REGIONS

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INTRODUCTION

Discussions about management of Vertisols traditionally emphasize their constraints. Vertisols are difficult soils to manage. Physical limitations to farming are numerous and complex and a high standard of management is essential to maintain consistent crop yields. It should be recognized, however, that these soils also have inherent advantages which should be equally stressed. A strategy for the development of management schemes must address ways to overcome their natural constraints while getting maximum benefit from their favorable features.

Land use constraints due to physical properties of Vertisols are widespread. Being made up of large amounts of smectitic clays, these soils have a very distinct hydrologic behavior. This includes high shrink-swell potential, low saturated hydraulic conductivity and extremely low infiltration rates upon wetting, preferential flow through cracks and macropores (bypass flow), very plastic and sticky consistency when wet, and gilgai microrelief that governs internal and external drainage (Dudal and Eswaran, 1988; Bouma and Loveday, 1988).

Practical consequences are numerous. The relatively narrow moisture range between the plastic, friable, and hard consistency states is one example. The consequence is that there are only brief periods of time during which the soil exhibits favorable conditions for tillage. Tillage operations when the soil is wet generate structural damage —shifts in pore size distribution toward finer pores and increased bulk density. Resultant slow internal drainage commonly causes anaerobiosis, denitrification, high volumes of surface runoff, and excessive erosion.

But Vertisols possess positive features related to water storage, chemical properties, and structural restoration. Total and available water retention is

usually high. This is a significant advantage for regions with a long dry season or unreliable rainfall patterns. Chemical properties are generally favorable for plant growth. This is attractive during periods of high costs for supplying nutrients. It is also a distinct advantage in remote areas of developing countries where availability of fertilizers or feasibility to buy them by farmers is low. Finally, there is evidence which indicates that long-term soil structural degradation accompanying cultivation is not as serious for some Vertisols as for medium-textured soils (Warkentin, 1982). Soil structure in these clay soils is more dynamic and resilient, mainly related to alternate wetting and drying, processes which occur naturally. Such a regenerative characteristic is particularly significant for intensive farming systems.

Potential crop productivity is high under optimal soil and crop management conditions. However, subutilization and low yields are widespread. It has been mentioned that differences between yields on commercial farms and yields on experimental fields are greater in Vertisols than in other soils. This is not always true, but wherever it does occur, it may be explained by the interaction of physical, economical, and social constraints. A comparison of practices used to deal with these problems on similar Vertisols but under different socioeconomic conditions may provide clues for development of more effective soil management recommendations and for reducing the gap between actual and potential yields.

The objectives of this review paper are (a) to outline some of the factors that control soil management of Vertisols in temperate regions, including both advantages and constraints, and (b) to discuss how soil scientists and farmers adjust soil management techniques and adapt them to the peculiar characteristics of Vertisols under different socioeconomical frameworks ranging from medium to high imput systems. Uruguay and Texas will be discussed for comparative purposes. Uruguay could be considered as an example of a highly mechanized, medium input farming system while Texas represents a totally mechanized, high input agricultural system. Although the emphasis will be on these two regions, examples from other temperate areas will be included as needed.

Vertisols are far from being a homogeneous group of soils (Bravant, 1987). They show a wide range in properties such as moisture regimes, structure, and chemical characteristics. Such variations result in differences in management requirements and potential productivity. This discussion will be directed primarily to deep, organic matter-rich, self mulching Pelluderts and Pellusterts from temperate climates. Emphasis will be on management of soil physical properties. Wet Vertisols are common in temperate regions too (Comerma, 1985) but they are not included in the discussion. Management of wet Vertisols is discussed by De Datta et al., (1988).

THE PHYSICAL ENVIRONMENT

Uruguay

Most Vertisols in Uruguay are fine, montmorillonitic, mesic, Typic Pelluderts (Typic Eutruderts by the proposed ICOMERT modification, see Comerma et al., 1988). They are associated in the landscape with Typic and Vertic

Argiudolls. They have been extensively surveyed, described and characterized (Lopez Taborda, 1967; Troeh, 1969; Carnelli and Guarinoni, 1976; Capurro and Ponce De León, 1980; Kaplán and Ponce De León, 1981; Lugo Lopez et al., 1985; Durán, 1985). They are deep, very dark soils with gilgai microrelief. Clay content ranges from 40 to 60%, usually increasing with depth. Organic matter content is relatively high, ranging from 4% to more than 8% under uncultivated conditions. A distinct granular or fine blocky structure (self-mulching) is widespread in topsoils which have not been degraded by cultivation.

Vertisols in Uruguay are usually found in two different topographic positions: (a) in almost flat, depositional surfaces; and (b) in gentle undulating sedimentary landscapes (1 to 4%, convex slopes). Vertisols on flatlands are most common throughout the central and northern part of the country, where basaltic materials are predominant. Normal gilgai is the rule. Vertisols on sloping lands, most common in southcentral and southwestern regions, are developed from Pleistocene-age, silty clay or silty clay loam textured, calcareous sediments. In this region, linear gilgai, with parallel or radiating waves oriented in the general direction of the slope (feather pattern), is prevalent. Microridges and microvalleys are almost always correlated with cyclic horizonation: the brown, calcareous subsoil is near the surface at the microridge and deeper than 70 cm beneath depressions.

Texas

Newman (1986) has reviewed Vertisols in Texas: all Suborders occur except Xererts. They are the dominant soils in both the Blackland Prairie and Coastal Prairie major land resource areas. Entic Pelluderts and Udic Pellusterts are common in the Coastal Prairie. Udic and Entic Pellusterts predominate in the Blackland Prairie.

Udic Pellusterts in Texas (Udic Eutrusterts by ICOMERT's proposal) are also dark and deep soils. They are often calcareous at or near the surface. Clay content ranges from 40 to 60%. They occur in nearly level to sloping lands, mainly within the 1 to 5% range. Most parent materials are calcareous (clays, marls, chalks, and shales) of Cretaceous or earlier origin. Gilgai, both normal and linear, is almost always present. There is a wavy boundary between the very dark gray or black upper horizon and the grayish brown lower horizons, similar to that described for Uruguayan Pelluderts. Organic matter content ranges from 3 to 6% under uncultivated conditions and self mulching properties are common.

The most apparent physical environment differences between Texas and Uruguay are climatic. Texas Vertisols occur in a dryer climate, with an average annual precipitation varying from 700 to 1000 mm. Vertisols on sloping lands have a ustic soil moisture regime intergrading to udic. Uruguay Vertisols occur in a subhumid environment, with 1100 to 1300 mm of total annual precipitation, distributed throughout the year. The most common soil moisture regime of sloping lands is udic. However, a three months period of moisture deficit occurs in most years, generally during the summer months (December - February), due to high evapotranspiration rates. Occasionally there are se-

vere moisture stress periods. Vertisols in Texas are also warmer: the most common soil temperature regime is thermic in Texas and mesic in Uruguay.

LAND USE

Socioeconomical factors, particularly location, strongly affect land use of Uruguayan Vertisols. Highly mechanized cereal agriculture (wheat, sorghum, and corn) is the prevailing land use in extensive areas in the southwest and Rio Uruguay littoral, while vegetable farms and orchards are common around Montevideo. Corn monoculture has been a traditional land use among small immigrant farmers, triggering severe land degradation. Sugarbeets are grown in the vicinity of a sugar processing plant although Vertisols are not well suited for production of root crops. Sugarcane is grown with success in the northwest region of the country, benefitting from a warmer and more humid climate. In the rest of the country, where traditional land use is grazing, extensive areas of Vertisols remain as rangelands.

Uruguayan farmers and soil scientists mutually recognize the comparative advantages and constraints of Vertisols. Vertisols are generally considered as highly productive soils, suitable for a wide range of alternative uses, due in part to high natural fertility and favorable topography. Workability emerges as the main constraint preventing full utilization. Problematical physical properties interact with an erratic rainfall, resulting in a wide array of management problems (seedbed preparation, weed control, aeration, trafficability). Vertisols also are considered excellent grazing lands by ranchers. However, an uneven forage production distribution, with lows in winter and maximum peaks in the spring, requires careful attention in adjusting stocking rates to avoid overgrazing.

Of the estimated 6 million hectares of Vertisols in Texas approximately 4.5 to 4.8 million occur in regions receiving 760 to 1150 mm of rainfall, most of which occur immediately before or during the growing season. Consequently, these soils are some of the more highly productive in the state. They also serve as the base on which several major cities are built. Dallas, Waco, Fort Worth, Austin, San Antonio, Corpus Christi, Beaumont, Houston, Temple, Victoria, and several other large cities are built primarily on these soils that have high shrink-swell potential. Millions of dollars of damage are caused to structures annually by the shrink-swell soils and many workmen lives are lost each year due to improperly shored trenches in these regions. Approximately 80% of the Vertisols are in farm and ranches. Of that amount about 50% are planted in cropland. Small grains dominate cropland uses throughout the Blacklands with wheat making up approximately 35% of the crops grown and oats approximately 15%. Hay and grain sorghum each constitute 20% of the cropland and cotton and corn each being 5% to 10% with the concentrations of cotton centered in the central portion of the Blackland Prairies.

In the coastal Bend area of Texas, the major crop accounting for approximately 65% of the cropland is grain sorghum. The rest is mainly corn and cotton making up approximately 14% each one. Relatively small amounts of wheat, hay, and oats are also produced. In the Upper Coast area, a more diverse land use pattern is found, with grain sorghum accounting for approxi-

mately 27% of the acreage, soybeans and rice approximately 22% each one, and corn, 15%. Other crops are cotton, hay, and small grains. Water erosion problems are much more common in the Blackland Prairies than in the Coastal Prairies due to steeper slopes, up to 5% or more. In the Coastal Prairies slopes are less and generally less than 2%, and water erosion is not a problem except in breaks into drainageways.

Extensive Vertisols exist in Australia under temperate climate. Such Pellusterts and Chromusterts occur throughout northeastern New South Wales and central and southern Queensland, particularly in the Darling Downs plains. Vertisols developed from Tertiary-age basalts, with an average annual precipitation between 500 and 800 mm, are among the most fertile and productive soils of the Australian wheat belt (McGarity, 1975). However, because winter rainfall is both low and unreliable, production of wheat is dependent on the capacity of these soils to store summer rainfall. Grain sorghum is an important summer crop followed by corn and soybeans. Commercial dairying and grazing are alternative land uses (Thompson et al., 1983; Clarke, 1986).

BASIC ELEMENTS FOR A MANAGEMENT SCHEME

Selected soil properties affecting Vertisol management

Soil consistency, organic matter, and exchangeable sodium

Vertisols exhibit extremes of consistency — they are very hard when dry and very sticky and plastic when wet. The period during which they can be worked under favorable conditions is so short that farmers with traditional tillage systems often cannot manage to find the opportunity to complete seedbed preparation . Factors affecting cohesion and adhesion forces include clay content, clay mineralogy, organic matter, and exchangeable cations.

Organic matter has a marked effect on soil consistency (Baver et al., 1972). In particular, it affects the amount of water needed to impart plastic properties. Increasing the organic matter level raises the moisture content of the plastic limit with important practical consequences because the farmer will be able to work the soil at a higher moisture content without destroying the soil structure. Thus, the number of work days when cultivations are possible without structure degradation increases.

Many Vertisols of temperate regions, particularly those uncultivated or cultivated only recently, have high organic matter contents (2 - 8%) (INTA, 1980; Russell, 1984; Durán, 1985). Furthermore, organic carbon reaches a steady state after several years of cultivation that is not as low as those for sandy or medium-textured soils. Capurro and Ponce de León (1980) reported 3% to be a new equilibrium level of organic carbon for a Typic Pelludert in Uruguay after several years of cultivation. The original level was 7%.

Part of this organic matter is strongly tied to smectitic clays. Micropeds in clay soils with high base saturation are held together by clay-polyvalent metal-organic matter bondings. The organic matter within these micropeds is physically inaccessible to microorganisms, and hence, not subject to rapid decomposition (Edwards and Bremner, 1967). Characterization of organic matter in Argentinan Pelluderts (Stephan et al., 1983) showed a long residence age, up to 4000 years, which might reflect the accumulation of very re-

sistant forms of organic matter, well protected by the clay matrix. These resistant complexes may have an effect on the dark colors (low values) which characterize many "pellic" Vertisols even under good aeration and relatively low organic matter conditions. They also influence soil consistency and self-mulching properties.

Exchangeable sodium is another factor affecting soil consistency. Some Vertisols have relatively low sodium saturation levels (ESP), in the range between 5 and 10%. Although these levels would not be detrimental to management of medium-textured soils, they have a distinct effect on smectitic systems, even in the presence of high amounts of calcium. Sodium-saturated smectites have rheological properties that differ significantly from calcium-saturated clays. They have greater shear strength, greater tensile strength, and the plasticity index also is larger (Warkentin and Yong, 1962, Dowdy and Larson, 1971, Baver et al., 1972; Yong and Warkentin, 1975). Smith (1959) reported that high amounts of sodium increased the dry density of clods and natural aggregates for the Houston Black Clay Udic Pellustert. Mukhtar et al. (1974) found that higher ESP resulted in decreased hydraulic conductivity and lower structural stability. Agassi et al. (1985) observed negative effects on infiltration rates and crust formation by raindrop impact at ESP's as low as 5% on Chromoxererts.

The effect of exchangeable sodium on physical properties and management of Vertisols has been recognized by soil scientists elsewhere. The Uruguayan soil classification system includes "sodic phases" for Vertisols with ESP's between 10 and 15% (Altamirano et al., 1976). The ESP is a diagnostic criterion for Vertisols in Entre Rios, Argentina, at the Family level (INTA, 1980). Australian soil scientists have done extensive research on this topic. Soils are considered "sodic" with ESP's between 6 and 15, and "strongly sodic" with ESP's greater than 15. The ESP value of 6 was suggested by general Australian experience as being associated with the onset of the hardsetting characteristics of surface soils and reduced permeability (Northcote and Skene, 1972). This value is significantly lower than the 15% currently included in Soil Taxonomy for the definition of a natric horizon (Soil Survey Staff, 1975). However, it must be pointed out that the effect of exchangeable sodium is not independent of other factors, such as electrolyte concentration of the soil solution (Mukhtar et al., 1974; Dane and Klute, 1977, Wilding and Tessier, 1988). In high electrolyte concentration systems, the influence of sodium on soil physical behavior is less distinct. The level of exchangeable magnesium may be another interacting factor (Emerson and Bakker, 1973).

Self-mulching and structural degradation

Management problems related with the effect of soil structure and consistency on tillage, are not uniform on Vertisols. For the self-mulching Vertisols these problems are less critical. The surface layer of these soils has a natural tendency to granulate. In cultivated fields, this granular structure is generated by the gradual disruption of clods. Exposed clods start parting into small blocks and granules; driving forces are wetting-drying and freezing-thawing cycles. Wetting-drying due to periodic light rainfall events, and freezing temperatures are frequent in many high latitude conditions.

Self-mulching properties are neither universal nor permanent features of Vertisols. The original term "grumosol" is derived from the Latin word

"grumus"; the term was intended to apply to all clay soils with a crumbly or self-mulching surface layer (Ahmad, 1983). The distinction between "grumic" and "mazic" classes was considered as a possible classification criterion for Vertisols in the "7th Approximation". Unfortunately, this idea was abandoned in Soil Taxonomy although it has again surfaced as a matter of discussion by the ICOMERT*. This distinction is still used in regional classifications and as a major criterion for land evaluation schemes (Beckmann and Thompson, 1960; Coughlan et al., 1987).

Promotion of annual structural conditioning of the topsoil through natural wetting-drying cycles should be a goal in any tillage system for self-mulching Vertisols. This can be achieved through early-in-the-season tillage and residue management, as a means for reducing the number of field operations. If self-mulching soils are repeatedly plowed during the dry, summer-autumn period to obtain a fine seedbed for winter crops through tillage, the self-mulched surface is destroyed or buried by inversion. Such a self-defeating practice should be avoided.

Long term conservation of self-mulching properties should be a parallel objective. Monoculture systems and clean fallow reduce the organic matter content. Tillage and harvesting operations carried out when the soil is wet cause structural degradation and self-mulching characteristics may decrease or disappear. There is experimental evidence from Typic Pelluderts in Uruguay and elsewhere that structural stability is high for Vertisols when compared with associated Mollisols and Alfisols (Bak and Cayssials, 1974 ; Kaemmerer and Sacco, 1977). However, both organic matter and structural stability decrease, and physical condition deteriorates, with long-term cropping (Arias and Battista, 1984; Hodgson et al., 1986).

The process of structural degradation is self-accelerated. It falls in the category of positive or self-enhancing feedback processes. A degraded physical environment affects vegetative growth. Root development is reduced. Plants extract lower amounts of water. As the soil remains wet for longer periods of time, there is higher chance that tillage operations will be carried out under suboptimal conditions. A progressively worsening situation therefore, can develop following a series of difficult seasons or inadequate soil management (Wilkinson, 1975). Even with sound soil management practices, sustained crop production heavily relies on the resilience of the soil to recover from structural damage. There is experimental evidence that would indicate high resilience in the structure of shrink-swell clayey soils. They may recover porosity and pore continuity after compaction and puddling by agricultural machinery, especially if a large proportion of the shrinkage is "structural" (Reeve and Hall, 1978). Regenerative trends in the structure of disturbed clayey soils when natural processes are not interrupted by cultivation practices have been reported by Croney and Coleman (1954), Goss et al. (1978), and McGowan et al. (1983). Bullock et al. (1985) reported structural restoration under minimum tillage. A model for structure regeneration has been proposed by Newman and Thomasson (1979). This potential for structure restoration due to shrinking and swelling, and biological activity (mainly earthworms), is a major factor in determining suitability of Vertisols for minimum tillage systems (Stengel et al., 1984).

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*See Comerma J.A., ICOMERT, 3rd Circular Letter, undated.

Erosion hazard

Soil erosion is a major constraint for sustained crop production in Vertisols of temperate regions (INTA, 1980; Mullins et al., 1987). Estimation of soil erodibility on the basis of the Wischmeier nomogram may be misleading in Vertisols (Puentes, 1983; Loch, 1984). High organic matter content and good aggregation in self-mulching Vertisols may result in determinations of low K values. However, risk of erosion remains high. One reason is the low saturated aggregate density (Loch and Donnollan, 1983). Young (1980) has noted that well aggregated clay soils tend to erode as aggregates and do not require clay dispersion. Another reason is the high runoff rate when the soil is wet. Infiltration is high when cracks are open but extremely low after crack closure, generating high volumes of runoff (Hein, 1969; Freebairn et al., 1984; Fiori and Martinez, 1985). In addition, Vertisols in sloping lands are prone to gully erosion. Once the process of gullying is initiated, gully development is very fast, being accelerated by mass slumping due to failure along cracks and slickensides. Gully erosion in Vertisols is another self-enhanced feedback process.

Soil Management for Sustained Farming Systems

Cropping systems

Crop rotation is a key component of the strategy for soil management in Uruguay. A farming system based on rotations between cereals and mixed pastures (grasses and legume species) maintains adequate soil physical conditions and increases yields with 40 to 60% savings in N fertilizers (Baethgen et al., 1980; Diaz et al., 1980). Farm income also is more stable. Fertilizer nitrogen is expensive in Uruguay. For the period 1960-1980, an average of 5 to 12 kg of wheat were needed to buy 1 kg of N, with peaks of 20 kg of wheat per kg of N in 1965-66. The recommended levels of N fertilizer in Uruguay for wheat in rotations with pastures range from 0 to a maximum of 30 kg N ha-1 (Oudri et al., 1976). Nitrogen fertilization may total up to 30% of the cost of establishing a field of wheat. The legume component of the pasture is responsible for the improvement of the N levels. Maintenance or improvement of soil physical properties due to the rooting system of the grass component is another advantage of the rotation system.

In southern Australia with predominantly winter rainfall, satisfactory land use systems based on crop-pasture rotations have been developed. The system, which includes legumes (mainly annual *Medicago* species) and integration of cropping with livestock production, is able to stabilize at a high steady-state soil organic matter level sufficient to maintain crop productivity and yield stability (Russell, 1984).

Under conditions of less expensive N, such as in Texas, the economic advantages of crop-pasture rotations are less apparent, and grain yields can be maintained under continuous cropping with adequate N fertilization. However, degradation of soil structure and soil erosion may affect long-term yield stability in the continuous cropping systems under conventional tillage. This problem can be addressed through reduced and minimum tillage systems.

Tillage

The extremes in consistency states described in a previous section result in the well-known constraints for tillage in Vertisols. Minimizing tillage operations is an appropriate strategy. Main objectives of tillage are: (a) conditioning a favorable environment for seed germination and root development; (b) enhancement of infiltration; and (c) weed control. It is useful to analyze how these multiple objectives can be achieved while reducing the number of tillage operations in Vertisols.

Conditioning seedbed and root environment. Self-mulching properties facilitate seedbed preparation in Vertisols. Timing of operations is important in this regard. Early tillage, immediately after harvest if moisture content allows, coupled with adequate residue management, promotes natural reconditioning of the soil through wetting-drying cycles. Several experiments reviewed by Baethgen (1982) in Uruguay confirm the advantages in yield of wheat due to early tillage treatments (end of February, for normal fall planting in June). These higher yields are explained by both a better structural condition in the seedbed, and a more favorable N balance due to a longer period of residue mineralization. Bare fallow land, particularly when crusted, may fail to dry out. Early ploughing also may be a remedy in this case, speeding up drying.

However, the self-mulching characteristics of topsoils does not solve all problems pertaining to seedbed conditioning, and an adequate seedbed is not always easy to achieve on Vertisols. Leslie (1965) examined factors responsible for failures in crop establishment in Australia. Field evidence collected by researchers at the Blacklands Research Center at Temple, Texas, shows that lack of uniformity at the emergence stage is a widespread problem in Vertisols and there is no answer yet to this problem. Two recent innovations to improve plant establishment are pre-germination of seeds and water injection (Russell, 1984).

Soil strength determines root development. Soil strength when Vertisols are wet is low, and should not be a hindrance for rooting, although aeration may be the limiting factor for root development under these circumstances. Several authors agree that bulk density would not be an important limiting factor to root growth in Vertisols (Warkentin, 1982; Willcocks, 1984); however, soil strength may be a constraint during extended dry conditions. Root pruning due to shrinking-swelling may be an additional problem. Unfortunately, if these problems occur, they cannot be fully addressed through tillage. Deep tillage of Vertisols, besides requiring high energy inputs, does not show long lasting effects. Its value is questionable. Under a rotation scheme, however, the root system of the grass component usually promotes a favorable structure throughout the whole rooting depth.

Soil water management. Plant-available water capacity is a function of potential soil water storage, storage replenishment, and plant water extraction. An important advantage of Vertisols is that they can hold an ample supply of water from rainfall and/or from irrigation, to provide for crop growth. Table 1 shows soil water characteristics for several Typic Pelluderts in Uruguay.

Table 1. Soil water characteristics of selected soils in Uruguay; soil water retained (% by volume) at indicated potentials (MPa) and available water (AW), in %. (From Capurro and Ponce de León, 1980 and Lugo Lopez et al., 1985).

Site	Hor.	Potential (MPa)				A.W.
		0.01	0.03	0.1	1.5	
Calagua	A1	33.6	31.6	30.2	25.0	8.6
	Bw	40.7	39.1	37.9	32.0	8.6
Tala	A1	42.2	40.2	38.9	24.5	17.6
	A2	40.2	37.9	36.8	24.3	15.8
Sarandi	A1	38.4	37.5	35.1	21.4	17.0
	A3	43.3	42.2	40.3	32.9	10.4

Water release between 0.1 to 1.5 MPa (AW) is significant. Coupling these results with morphological observations, the authors estimate between 50 and 75 mm of available water in the root zone (Capurro and Ponce de León, 1980; Lugo Lopez et al., 1985). Stace et al. (1968) reported 110 mm of stored available water for Vertisols in Australia.

To profit from the high water storage capacity, this storage must be periodically replenished. There is evidence showing that plant available water capacity in Vertisols is usually limited by rainfall acceptance rather than by water holding capacity (Loveday and McIntyre, 1966; Farbrother, 1972; McCown et al., 1976). Natural proccesses such as cracking and self-mulching have important effects on infiltration rates and on the overall water balance. Cracking may entirely control water entry into the soil under dry conditions (Bouma and Loveday, 1988). Self-mulching has influence on increasing infiltration and preventing rapid evaporation. Tillage also can be used to manipulate moisture replenishment. Cultivation can be done to enhance surface water retention — a rough surface can absorb high-intensity rainfalls, particularly when dry (Yule, 1987). Adequate infiltration rates can be maintained through tillage systems that retain crop residues at the soil surface, avoid compaction, and protect topsoil structure.

Weed control. Weed control emerges as one of the most important reasons for tillage in Vertisols in temperate regions. *Cynodon dactylun* is a critical problem for crops and pastures in Uruguay. In Texas, principal weeds in row crops are *Sorghum halepense* and *Amaranthus palmeri*. In small grains, main weeds are *Rapistrum rugosum* and *Lolium perenne* and in pastures, *Gutierrrezia texana* and *Prosopis glandulosa*. Weed infestation is a major constraint when mechanical control during the growing season is limited by the risk of degrading soil structure through traffic on wet soil. Weeds also are a problem for stubble mulch and other reduced tillage systems.

Herbicides may be specially suited under these circumstances. Timely herbicide spraying can be highly effective, for example, to control weed growth when the soil is too wet for cultivations, or to allow rapid post-harvest weed control prior to double-cropping. However, chemical control is not always economically feasible and may have negative environmental effects. In many circumstances, combining herbicide applications with tillage operations when possible is an appropiate approach. If tillage is to be used for weed control, it should be as shallow as possible (Willcocks, 1984). Shallow tillage con-

trols weeds and also reduces seedbed drying. Timing of cultivation is also critical. Ideally it should not be before sufficient rain has fallen to replenish soil moisture and germinate the first flush of weeds, which can subsequently be killed by the cultivation (Loch and Coughlan, 1984).

Reduced tillage systems and residue management. The ability of Vertisols to shrink and swell is an important attribute for Vertisols under minimum cultivation systems (Ellis et al., 1979; Stengel et al., 1984). Compaction is a serious concern in reduced tillage, and particularly, zero-tillage. Swelling clay soils, in contrast with medium-textured or sandy soils, may recover porosity and pore continuity after wetting and drying due to their more dynamic structure (Blackwell et al., 1985).

Management of crop residue at the soil surface is a key element of any reduced tillage system. Experience shows that farmers are able to manage crop residue left on the soil surface by their choice of implements and frequency of cultivation. Disks implements should be avoided. They bury from 30 to 70% of surface residues during each operation (Fenster, 1977). In addition, disk type implements pulverize soils, reduce surface roughness, negatively affect self-mulching properties, and may generate plowpans. Unfortunately, disks are frequently used both in Texas and Uruguay because farmers take advantage of their capability to be used under adverse soil conditions.

The effects of reduced tillage on soil erosion are highly significant. Soil movement is reduced by 50-90% if mulch residues of 30% or more are maintained during the erosive periods (Moldenhauer et al., 1983; Freebairn and Wockner, 1986). Residues of this magnitude can be achieved with currently available equipment and stubble yields obtainable in many temperate regions.

A successful reduced tillage system for Vertisols requires adequate management skills, a planter able to place seed through a stubble layer into soil which may be plastic when wet or cloddy when dry, and an adequate approach for weed control.

Gerik and Morrison (1984) obtained similar soil water storage and sorghum grain yields with conventional and no-tillage systems on a swelling clay soil in Texas. Similar results were obtained with wheat except with a very dry year (Gerik and Morrison, 1985). Even without significant yield advantages, no tillage has a potential for the region because production costs are lowered and narrow-row cropping is possible.

There is a recent trend in Australia toward reduced tillage systems for Vertisols. Experimental results show advantages in yields when these systems are compared with clean tillage (Mullins et al., 1987). Freebairn et al. (1986) describe a versatile planter developed for Australian conditions. The machine is able to successfully operate through up to 6 t ha-1 of crop residue under a wide range of soil moisture conditions. This is achieved using a combination of a 55 cm diameter, smooth coulter, a narrow spear point opener, and a narrow, overcenter, single ribbed, variable weight press wheel. This assemblage avoids mud build up. Narrow point tines are used to minimize smearing, a common problem with clayey soils. Chemical weed control is used.

In Uruguay, progressive farmers know the technology and a few of them use minimum tillage on sandy and medium-textured soils. However, inadequate machinery to till clayey soils, and weed control problems are constraints that hamper the diffusion of this innovation. In addition, a farmer may

have to change his whole farming system, not just the tillage methods, to obtain the maximum benefit from the improved system.

Preventing soil erosion

Minimum tillage has proven very effective in erosion control. Several conservation tillage practices such as stubble mulching, ridge-planting, paraplow, and no tillage are discussed by Unger and Stewart (1988). Two most common technical reasons for not using minimum tillage systems are lack of adequate machinery and low amounts of residues available. Under these circumstances, the goal should be to increase infiltration and remove excess runoff from fields at non-erosive velocities. To achieve these objectives, farmers have different tillage and crop management alternatives combined with control structures such as terraces and grassed waterways.

High erosion rates observed within contour embankments or terraces in Vertisols in Australia and Uruguay indicate that these engineering structures by themselves are insufficient in some areas to stabilize the soil under erosive rainfall (Petraglia et al., 1982; Freebairn and Wockner, 1986). Temporary surface storage of water to reduce runoff can be increased through contouring, ridging, and furrow diking. Tillage orientation has little effect on sediment concentration but contour operations substantially reduce total runoff and soil losses (Loch and Donnollan, 1983). Contouring is recommended both in Uruguay and Texas as a simple, inexpensive practice to control soil erosion. It provides protection against erosion from low to moderate intensity storms in gently undulating fields. Significant decrease in runoff was obtained with graded-furrows on Texas Vertisols (Richardson, 1973). Furrow diking requires special machinery to stablish dikes or ridges across furrows. It has been found effective as a soil and water conservation practice on gently sloping lands of Texas, where soil moisture conservation is first priority (Unger and Stewart, 1988).

Conventional row spacing for most crops in Texas has been 90 to 100 cm since periods of horse-drawn equipment. In the Blackland Prairie, dryland grain sorghum with narrow-row (50-cm) spacing has consistently out-yielded sorghum with conventional row spacing (100 cm) by 15-20% when weeds are controlled and plant population is approximately the same (Adams et al., 1976). Adams et al. (1978) assessed the effect of narrow and conventional row spacing of grain sorghum on runoff and erosion from field size areas. Plant canopy from sorghum in narrow rows provided protection against raindrop impact earlier than sorghum in conventional row spacing. Maximum canopy cover was 81% of the soil surface for narrow rows, and 46% for conventional spacing. Runoff was 45% less and soil loss was 39% less from narrow-row grain sorghum than from conventional row spacing. Narrow-row cropping is not possible with clean tillage where sorghum must be cultivated to control weeds.

SUMMARY AND CONCLUSION

The high potential productivity of Vertisols in temperate regions has been recognized by both farmers and soil scientists. Some soil management strategies and farming systems have been adapted. But common principles of

soil management developed for medium-textured soils, do not apply for Vertisols. This hampers the development of appropriate technology and requires a high degree of ingenuity and creativity. There still exists a wide potential for basic and applied research on Vertisols management.

No single farming system appears universally applicable for Vertisols from temperate regions on a worldwide basis. Similar soil management principles are valid for the reasonably homogeneous category of deep, self-mulching, and organic matter rich Uderts and Usterts discussed in this paper. However, the application of these basic principles is site specific. Socioeconomical aspects are also involved. Factors such as location, social customs, price of fertilizers, and availability of appropriate machinery, play an overriding role in determining land use.

Regional evaluation of alternative cropping systems for Vertisols must be carried out both in agronomic and socioeconomic terms. The former will determine if the systems successfully overcome soil constraints and benefit from the opportunities offered by Vertisols. How systems take advantage from the natural fertility and potential available water capacity, and how critical soil constraints have been properly identified and addressed, are some of the questions to be considered at this step. Farming system sustainability is an additional key element. The ultimate criterion of this biological evaluation will be, of course, crop productivity. The socioeconomic evaluation must cover both economic and managerial aspects from a practical standpoint. Crop productivity, as assessed through the agronomic evaluation, must be expressed in monetary values and net returns. Farm resources other than land and cash must be incorporated into the evaluation. Due to their physical properties, timing of operations and managerial skills are key elements for Vertisols. Detailed schedules of activities must be prepared and compared to avoid conflicts in the utilization of labor and/or machinery. Finally, the evaluation must include stability and risk analysis, both on agronomic and economic terms. This way, results will be meaningful to farmers.

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Chapter 9

FORMS OF PHOSPHORUS AND PHOSPHORUS SORPTION IN NORTHERN CAMEROON VERTISOLS AND ASSOCIATED ALFISOLS

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INTRODUCTION

Despite reports that Vertisols are low in phosphorus (Sanchez, 1976), little effort has been made to address this problem in the semi-arid tropics where Vertisols cover about 260 million hectares (Ahmad, 1983).

Very few studies have been carried out on P forms or P-sorption in the semi-arid tropics where Vertisols and Alfisols predominate. This can be attributed to the generally high base status of these soils and, hence, an absence or paucity of amorphous Fe- and Al-oxides. Sanchez and Uehara (1980) demonstrated that organic matter, clay content, clay mineralogy and flooding influenced P adsorption. Other studies (Ryan et al., 1985; Freeman and Rowell, 1981) have demonstrated that P tends to precipitate on calcite surfaces. Burnham and Lopez-Hernandez (1982) reported that Pellusterts of Venezuela with significant extractable aluminum fixed large amounts of phosphorus.

The importance of P reactions in soil is largely due to its agronomic role. As solutions containing P come into contact with soil, the concentration of P in solution decreases. The decrease is attributed to sorption (adsorption/precipitation) on soil surfaces. The sorptive character of P is important because it serves as a guide for determining the amount of P available to plants and the fate and effectiveness of P-fertilizers (Probert, 1983).

Phosphorus moves to the roots largely by diffusion (Barber, 1962; Lewis and Quick, 1967; Olsen and Watanabe, 1963). Soil water and bulk density influence tortuosity and cross sectional area for diffusion. Diffusion increases with decreasing bulk density and increasing soil water content (Heslep and Black, 1954: Hira and Singh, 1977; and Schaff and Skogley, 1982).

With the foregoing statements, it is apparent that Vertisols, because of their high clay contents, dense and compact nature and low porosity, warrant investigation into the fate of applied P.

Phosphorus adsorption isotherms have become increasingly important tools for estimating phosphate availability and adequate soil solution concentration levels (Ozanne and Shaw, 1967; Rennie and McKercher, 1959; Thompson et al. 1960; Rajan and Fox, 1972; and Fox and Kamprath, 1970). Rajan and Fox (1972) indicated that the phosphate adsorbed by soils at the equilibrium P-concentration associated with any given yield is an estimate of the P requirement for that yield. To obtain dependable values, the conditions for the kinetics of P-sorption are very important. Equilibrium time, ionic environment, and temperature (Probert, 1983; Rajan and Fox, 1972; and Fox and Kamprath, 1970) appear to be the most important parameters influencing P-adsorption.

The Langmuir isotherm has been used to describe P-adsorption data, though only within a limited P concentration range. This has been because its derivation is theoretically feasible and it gives parameters which have physico-chemical significance (Olsen and Watanabe, 1957; Holford et al., 1974). Recent studies, however, have suggested that soil P-adsorption data fit the curvilinear rather than linear Langmuir isotherms (Gunary, 1970; Bache and Williams, 1971; Holford et al., 1974).

There is no concensus yet as to what modification of the Langmuir equation best corrects for curvilinearity and gives the best P-adsorption maximum. Harter and Baker (1977, 1978) have proposed that the concentration of desorbed ionic species in solution will influence the adsorbed species and cause curvilinearity of the linear transformation of the Langmuir isotherm, and hence, give an underestimation of the P-adsorption maximum. The modification of the Langmuir equation by the latter investigators to account for the desorbed species has been challenged by Holford (1978) who showed that the modified equation gave the same shortcomings as the traditional (basic) Langmuir isotherm i.e. an underestimation of the P-adsorption maximum.

Veith and Sposito (1977) and Sposito (1982) have demonstrated that fitting experimental data to the Langmuir equation gives no information about the chemical mechanism of the sorption reaction.

The purpose of this study was to:

1. determine the amounts of total, organic and NH_4HCO_3-DTPA extractable P in Vertisols and Alfisols of northern Cameroon;
2. determine the capacity of surface samples to sorb inorganic P, evaluate the applicability of the Langmuir equations in describing the P-adsorption isotherms, and to relate the P fixing capacity of these soils to various soil factors; and
3. determine if the phosphate held on the high energy sites approximates that at a given equilibrium solution concentration for forest regeneration.

MATERIALS AND METHODS

Soil pedons of six Vertisols and one Alfisol in northern Cameroon were collected for this study (Fig. I). These soils are comprised of Andirni (Entic Pellustert); Louba Louba and Maga (Typic Pellusterts); Laf and Lam (Entic Pellusterts); Kousserie (Entic Chromustert); and Mora (Arenic Haplustalf).

The Andirni, Louba Louba, Maga and Kousserie soils are developed from Quaternary lacustrine sediments on a seasonally flooded lacustrine plain. The Laf and Lam soils have developed from upland Precambrian schist. The Mora soils were developed from Precambrian granite.

The climate of northern Cameroon is semi-arid with a marked wet and dry season. Mean annual rainfall and temperatures average 600-700 mm and 27-28 C, respectively. The moist color of the surface horizons of these soils are generally dark-gray (1O YR 2/1) to gray (1O YR 4/1).

Bulk soil samples were air-dried and coarse fragments were separated by passing the fine earth fraction through a 2 mm sieve. Particle size distribution, cation-exchange capacity (CEC), extractable bases, soluble salts and pH were determined by standard procedures (Soil Conservation Service, 1984). Organic carbon was determined as the difference between total carbon by dry combustion (Allison, 1965) and carbonate carbon by the Chittick procedure (Dreimanis, 1962). Amorphous Al and Fe were determined by the ammonium oxalate extraction method described by McKeague and Day (1966). Total surface area (<2 mm soil fraction) was determined by the ethylene glycol monethyl ether (EGME) method adapted from Carter et al. (1965). External surface area was determined by the nitrogen adsorption BET method described by Brunauer et al. (1938).

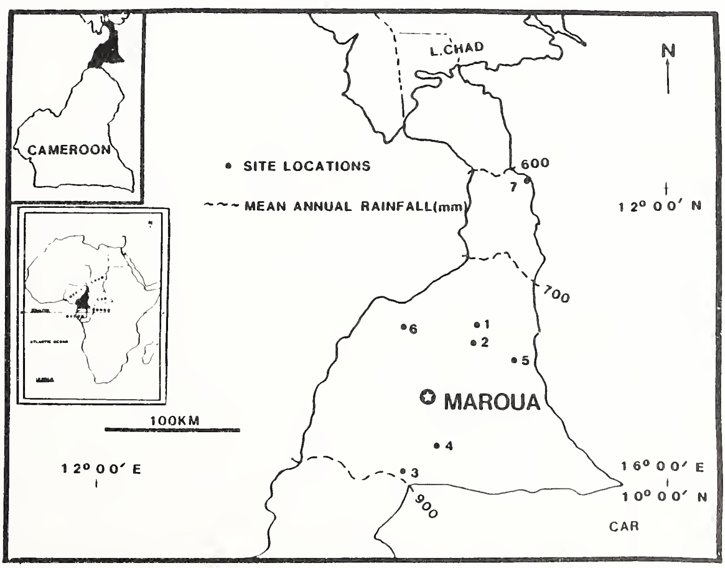

Fig. 1. Map of northern Cameroon showing site locations: 1 = Andirni; 2 = Louba Louba; 3 = Lam; 4 = Laf; 5 = Maga; 6 = Mora; and 7 = Kousserie

The physical and chemical properties are summarized in Tables 1 and 2. Mineralogical determinations were according to Brewer (1976) and Jackson (1956). The clay fraction of the soils developed from lacustrine sediments is composed of smectite, kaolinite, vermiculite, mica, quartz and feldspars. Soils developed from upland schist are similar to their lacustrine counterparts except, in addition, they contain chlorite and hydrobiotite. Detailed mineralogy studies are provided elsewhere (Yerima, 1986).
Phosphorus sorption isotherms were determined by the method of Fox and Kamprath (1970).

Data for plotting P-sorption isotherms were obtained in a similar manner to the kinetic study, except the equilibrium time was 228 hrs. Also, 0.01 M KCI was used as the support solution and KH_2PO_4 as the source of P. The initial P concentrations in the KCI solutions for the surface horizons of all the soils were 10, 20, 30, 40, 50, 100, 200, 300, 400 and 500 μgP/ml.

EVALUATION OF EXPERIMENTAL DATA

Phosphorus sorbed per unit mass of adsorbant was calculated and plotted in the single phase (basic) Langmuir isotherm form as C/Pa vs C, where C is final solution concentration in equilibrium solution (μg/ml) and Pa = amount of sorbed P(μg P/g soil) according to the equation:

$$C/Pa = C/PAM + 1/PAMK. \tag{1}$$

PAM = maximum adsorbed P on soil (μg/g soil) = 1/slope, and K is a constant related to the energy of adsorption and is expressed as slope/intercept. The above equation assumes that P is adsorbed on a uniform surface.

When it is assumed that adsorption is occurring on two different surfaces with different energies of adsorption, the two-surface Langmuir equation best describes this relationships and is given by the following equation:

$$Pa = [K'PAM'\,C/1 + K'C] + [K''PAM''\,C/1 + K''\,C] + \ldots + .. \tag{2}$$

Where K′ and K″ are bonding energies for the high and low energy sites, respectively. Phosphate-adsorption maxima (μg/g soil) for the high and low energy sites are expressed as PAM′ and PAM″, respectively, and C and Pa terms are as given in equation (1). For the plots and regression analyses, the sorbed P was not adjusted for pre-existing adsorbed P because of the low values of the latter and the insignificant difference when these adjustments were made (Yerima, 1986).

Statistical analyses were determined using SAS Institute User's Guide: Basics (1982) and SAS Institute User's Guide: Statistics (1982) and procedures by Neter and Wasserman (1974).

RESULTS

Total, inorganic, organic and NH_4HCO_3-DTPA extractable P are presented in Table 2. Total P values range from 152 to 595 μg P/g. Total P values

Table 1. Physical and chemical properties of selected horizons of some northern Cameroon soils.

Horizon	Depth	Particle Size Distribution (mm) Sand 2-.05	Silt .05-.002	Clay <.002	Organic Carbon	pH (H_2O) 1:1	NaOac CEC	Ammonium oxalate extractable Al	Fe	Surface Area (<2 mm) Total	External
	cm	%					meq/100g	%		m^2/g	
ANDIRNI											
A1	0-23	18.7	20.1	61.2	0.66	6.0	35.8	0.25	0.36	234	81
A3	48-70	15.2	18.1	66.7	0.51	6.6	39.0	0.27	0.21	250	—
2BCt	115-170	55.6	15.5	28.9	0.15	6.9	23.6	0.13	0.05	104	—
LOUBA LOUBA											
A1	0-15	10.6	21.2	68.2	0.98	5.6	38.1	0.30	0.62	260	78
Bw	76-100	14.4	17.7	67.9	0.61	6.6	37.3	0.21	0.25	259	—
2BCtk2	175-185	59.2	16.1	24.7	0.18	8.1	14.2	0.14	0.03	108	—
LAM											
Ap	0-15	17.4	33.7	48.9	1.27	7.8	41.3	0.30	0.12	265	66
Bk2	85-114	14.0	32.9	53.1	0.66	8.0	42.6	0.12	0.17	278	—
Ck	200-240	30.7	53.8	15.5	0.18	8.3	23.7	0.09	0.04	130	—
LAF											
Ap	0-19	18.8	42.1	39.1	0.84	7.1	27.8	0.24	0.10	190	45
Bk1	87-139	16.6	38.7	44.7	0.56	7.0	28.4	0.26	0.09	201	—
Bk4	216-255	22.1	31.8	46.1	0.20	8.1	35.7	0.23	0.06	223	—
MAGA											
A1	0-20	15.4	32.6	52.0	0.67	5.7	32.6	0.22	0.46	193	60
Bw2	97-141	11.3	30.1	58.6	0.35	7.5	31.3	0.22	0.15	223	—
BC	216-260	15.8	31.2	53.0	0.08	7.1	26.5	0.14	0.08	205	—
MORA											
Ap	0-10	70.7	20.9	8.4	0.55	6.8	6.6	0.10	0.04	31	5
2Btkl	100-131	43.8	30.6	25.6	0.24	7.7	16.1	0.10	0.04	112	—
2Btk3	170-215	43.8	32.2	24.0	0.23	8.0	16.8	0.10	0.03	100	—
KOUSSERIE											
A1	0-16	40.6	28.3	31.1	0.81	6.8	18.6	0.15	0.18	104	48
Bw2	70-107	46.8	29.4	23.8	0.22	8.1	13.7	0.10	0.06	94	—
2CBt	131-162	59.6	20.9	19.5	0.20	8.1	11.3	0.11	0.10	79	—

Table 2. Forms of P in selected horizons of the Andirni, Louba Louba, Lam Laf, Maga, Moral and Kousserie soils.

Horizon	Depth	Phosphorus				Amorphous			
		Organic	Inorg.	Total	Extract.	Al	Si	Fe	Total
	cm	(µg/g soil)				%			
		ANDIRNI							
A1	0-23	82	324	406	1.0	0.25	0.09	0.36	0.70
A3	48-70	73	252	325	1.8	0.27	0.09	0.21	0.57
2BCt	115-170	30	157	187	0.9	0.13	0.05	0.05	0.23
		LOUBA LOUBA							
A1	0-15	88	480	568	1.5	0.30	0.08	0.62	1.00
Bw	76-100	56	521	577	2.1	0.21	0.08	0.25	0.54
2BCtk2	175-185	23	160	183	0.3	0.14	0.04	0.03	0.21
		LAM							
Ap	0-15	64	130	194	0.2	0.30	0.09	0.12	0.51
Bk2	85-114	30	205	235	0.1	0.12	0.14	0.07	0.33
Ck	200-240	5	590	595	0.4	0.09	0.03	0.04	0.16
		LAF							
Ap	0-19	53	127	180	0.3	0.24	0.05	0.10	0.39
Bkl	87-139	30	122	152	0.1	0.26	0.06	0.09	0.41
Bk4	216-255	—	—	188	0.2	0.23	0.05	0.06	0.34
		MAGA							
A1	0-20	102	263	365	1.3	0.22	0.05	0.46	0.73
Bw2	97-141	66	188	254	0.2	0.22	0.07	0.15	0.44
BC	216-260	63	197	260	0.3	0.14	0.05	0.08	0.27
		MORA							
Ap	0-10	34	108	142	1.3	0.10	0.01	0.04	0.15
2Btkl	100-131	26	83	109	0.6	0.10	0.03	0.04	0.17
2Btk3	170-215	22	96	118	1.1	0.10	0.02	0.03	0.15
		KOUSSERIE							
A1	0-16	89	167	256	1.8	0.15	0.03	0.18	0.36
Bw2	70-107	55	120	175	1.1	0.10	0.03	0.06	0.19
2CBt	131-162	39	116	155	0.7	0.11	0.03	0.10	0.24

were much higher for soils developed from lacustrine material (Andirni, Louba Louba, Maga) compared to those developed from Precambrian schist (Lam and Laf) and Precambrian granite (Mora). Because these soils have never been fertilized, organic-P and mineral components constitute the sources of phosphorus.

Inorganic P values ranged from 116 to 590 µg P/g. Because the pH of these soils is generally slightly acid to alkaline, indicating limited weathering, it appears that the inorganic P is largely in the form of Ca-P.

Organic P values ranged from 5 to 102 µg P/g. Organic P values are higher for the lacustrine clay soils than those of their Precambrian schist counterparts. These values generally decrease with depth in conformity with observations by Probert (1983) for Australian soils. Organic P distribution is correlated with organic carbon distribution.

Ammonium Bicarbonate-DTPA Extractable P

Extractable P gives a measure of the quantity of P available for use by plants in soils. Extractable P is dependent on the ability of the solid phase phosphorus for replenishment of the solution phase P (Fox and Kamprath, 1970). The extractable P values are generally higher for the A and B horizons of the slightly acid soils developed on the seasonally flooded lowlands and much lower for soils developed from schist and granite. The soils developed from schist and granite contain $CaCO_3$ both as nodules and in finely divided powder forms in subsoils. In these calcareous systems, P may be precipitating as Ca-P, hence, reducing the amount of solution P. Islam and Elahi (1954) observed that soils subject to waterlogging had increased concentrations of extractable P. They attributed the increase to the reduction of Fe^{+3} phosphate to more soluble Fe^{+2} phosphate. Patrick (1964) also observed that the reduction of Fe^{+3} oxides may release occluded P, and increased its availability.

The extractable P values using the NH_4HCO_3-DTPA range from 0.1 to 2.0 μg P/g for all Vertisols of this study and are classified as low for cultivation of corn, sorghum, small grains and grasses (Soltanpour and Schwab, 1977). These values are very similar to those reported for Grumusols (Vertisols) of the Coast Prairie of Texas (Kunze et al., 1963) using 0.5 M sodium bicarbonate (Olsen and Sommers, 1982). The low values of extractable P for northern Cameroon Vertisols are consistent with observations by Sanchez (1976) for Vertisols in the tropics which are deficient in P.

Phosphorus Kinetics: Influence of Reaction Time on P-sorption

Phosphate-sorption was calculated for the different times of equilibrium. Sorption patterns (Fig. 2) were generally characterized by initial fast reactions followed by a slow reaction and is consistent with prior literature (Fox and Kamprath, 1970; Rajan and Fox, 1972; Haseman et al., 1950; and Kurtz et al., 1946). The initial fast reaction may be due to an exchange adsorption of HPO_4^- ions for OH^- ions on the surface of the soil particles (Haseman et al., 1950 and Low and Black, 1950). The slow reaction may be a continuous phase of Fe and Al-P, with the metal ions derived from a gradual breakdown of clay minerals and hydrous oxides (Haseman et al., 1950; Low and Black, 1950). The data from the equilibrium time study are presented as a plot of P-sorbed versus time (Fig. 2). These data indicate that for these soils, sorption was 85 to 88% completed after 50 hrs of equilibrium (based on 230 hrs = 100%). The Mora (Alfisol), with the lowest clay content (8.4%), was used to determine the P-sorption behavior for the low clay range for the kinetic study. Mora soil P sorption was approximately 85% complete after 30 minutes of equilibration.

When P-sorption was compared among the three soils, it was observed that sorption was related to the amount of clay and amorphous material. P-sorption decreased in the following order: Louba Louba (68% clay and 1% amorphous material) > Lam (40% clay and 0.50% amorphous material) > Mora (8.4% clay and 0.2% amorphous material) (Yerima, 1986).

The rapid sorption of P by the Louba Louba soil was probably due to the small amount of P added in relation to the sorption maximum. Because the

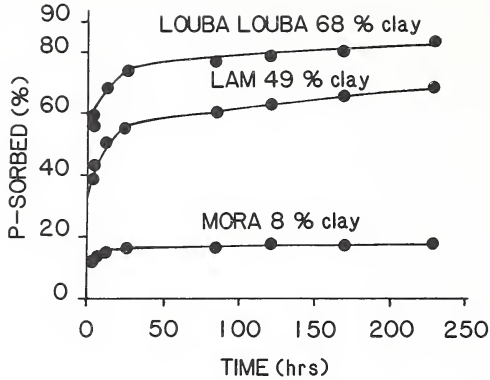

Fig. 2. Plot of P-adsorbed versus time in selected northern Cameroon soils equilibrated with 100 μg P/ml.

Mora soil is very coarse textured, faster equilibrium was attained in this system due to rapid saturation of exchange sites with the equilibrating solution.

The Lam and Louba Louba soils are very compact and dense and have high water retention energies due to their smectitic mineralogy. The slow approach to equilibrium may be attributed to a slower rate of equilibrium of P through extremely small pores of stable aggregates. Observations by Fox and Kamprath (1970) indicated easier accessibility of P to clay surfaces when clay is dispersed throughout sand media.

The Langmuir isotherms for these soils have a similar shape, except that of the Lam soil which contained free calcium carbonate. Langmuir isotherms based on the sorption data for the Lam soil were very erratic (Fig. 3). This relationship probably indicates that both adsorption and precipitation are operational in the carbonate system (Freeman and Rowell, 1981). Ryan et al. (1985) observed that in calcareous soils solid phase calcium carbonate is believed to govern P reactions. The existence of fine carbonate powder in the Lam soil may well explain this behavior.

Bonding energies for the lacustrine clay soils (Table 3) (Andirni, Louba Louba, Maga and Kousserie) are directly related to the P-sorption maximum. Increasing bonding energies were related to increasing clay content, amorphous mineral content, and external and internal surface areas. Bonding energy was lower, while the P-sorption maximum was higher in the calcium carbonate-rich Lam soil; this phenomenon is due to both greater precipitation and adsorption in the calcareous Lam soil, than in the non-calcareous soils.

Alternating reducing and oxidizing conditions for seasonally flooded soils will increase amorphous Fe oxide contents. This increase yields large surface areas conducive to increased adsorption maxima and high bonding energies.

Phosphate Sorption Relations

Due to the heterogeneous nature of the phosphate sorbing system, more than one soil parameter can account for the adsorption process. Phosphorus

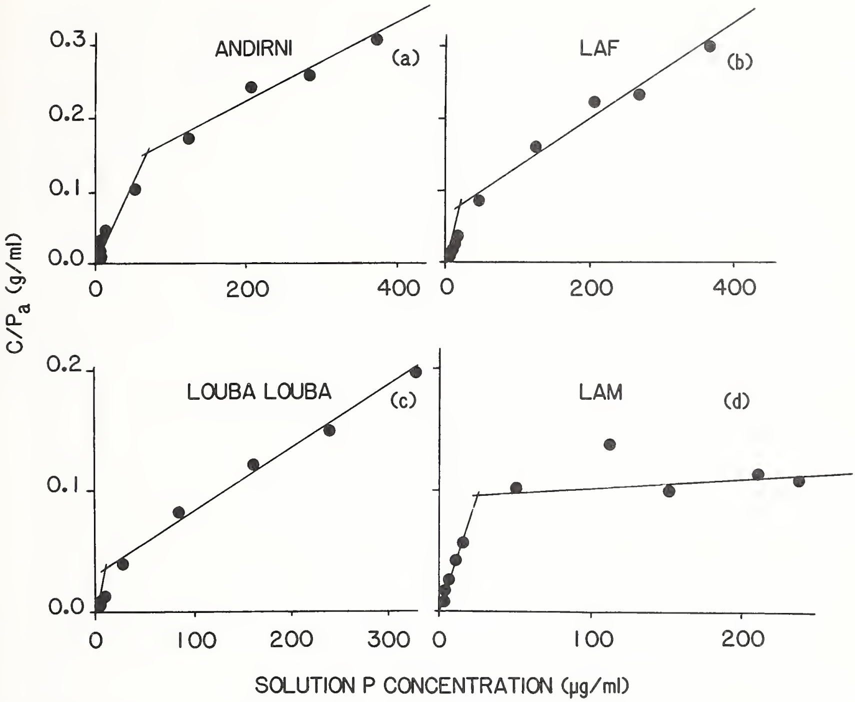

Fig. 3. Langmuir plots of concentration of P remaining in solution/P-adsorbed per gram of soil (C/Pa) versus concentration of P remaining in solution for selected northern Cameroon soils.

Table 3. Langmuir equations, correlation coefficients, P-adsorption maxima and bonding energies calculated from the basic Langmuir equation for selected northern Cameroon soils.

Soil Series	Adsorption Maximum	Bonding Energy $K \times 10^3$	Langmuir Equation+	Correlation Coefficient
	μg P/g soil	ml/μg P		
Andirni	1282	25.9	Y = 0.0301 + 0.00078X	0.939
Louba Louba	1695	60.1	= 0.0098 + 0.00059X	0.975
Lam	2564	11.4	= 0.0344 + 0.00039X	0.566
Laf	1266	31.4	= 0.0252 + 0.00079X	0.952
Maga	1667	40.1	= 0.0150 + 0.00060X	0.959
Mora	160	95.5	= 0.0654 + 0.0062X	0.980
Kousserie	1031	10.8	= 0.0900 + 0.00097X	0.879

+Y = log P-adsorbed on soil (g P/g soil); X = P remaining in solution (μg P/ml).

adsorption maxima (PAM) derived from the Langmuir (Basic) equation were evaluated for dependency on Fe and Al-oxides, organic carbon, percent clay, total surface area and other soil properties through regression analyses. Plots of PAM versus clay indicated a curvilinear relationship. When simple linear equations were used to fit the data, the equations obtained demonstrated a lack of fit as indicated by observed trends in the residual plots (Yerima, 1986).

Though a more linear relationship was obtained between log PAM and the respective logarithmically transformed independent variables, simple linear and multiple linear regression equations obtained using these transformed variables still demonstrated a lack of fit. The high adjusted r^2 (r^2a) values (Table 4a) are deceiving since the resulting plots were curvilinear. Equations containing a quadratic (power series) component gave a good fit as demonstrated by plots of the residuals (Yerima, 1986). When the quadratic models were used, greater than 92% of the variance in phosphate sorption could be accounted for by total surface area, external surface area, amorphous alumimum, and percent clay.

External surface area, total surface area and percent clay are interrelated. Cation exchange capacity is dependent on total surface area which in turn is dependent on type of clay, clay amount, particle size, and the quantity of amorphous species in the system. External surface area and internal surface area are also dependent on clay type, particle size, amount of clay, as well as the quantity of amorphous oxides. Some investigations (Coleman, 1944; Truog, 1955) have shown that P-fixation by clay minerals is related to the Al content of the clays. Ellis and Truog (1955) observed that the P-fixation properties of montmorillonite were nullified after Fe and Al were removed.

Table 4. Multiple and simple linear regression equations relating the P adsorption maximum (PAM) derived from the Langmuir equation to some physical and chemical properties of northern Cameroon soils.+

Dependent variable	Intercept	Coefficient	Variable	n	r^2a
		Linear (a)			
PAM	= 4.90	−0.304	pH	6	0.069
	= 3.40	2.48	log OC	6	0.182
	= 3.48	0.73	log AFE	6	0.657*
	= 4.27	1.97	log AAL	6	0.750**
	= 0.70	1.06	log TSA	6	0.907**
	= 1.23	1.12	log PCL	6	0.922**
	= 1.61	0.85	log ESA	6	0.943**

Dependent variable	Intercept	Coeff. (X1)	Variable (X1)	Coeff. (X2)	Variable (X2)	n	R^2a
			Multiple linear (b)				
PAM	= 4.12	1.31	log AAL	0.322	log AFE	6	0.749*
	= 1.04	0.940	log TSA	0.114	log AFE	6	0.884**
	= 1.57	0.872	log ESA	−0.022	log AFE	6	0.924**
	= 1.96	0.756	log ESA	0.275	log AAL	6	0.930**
	= −2.84	2.05	log TSA	−2.02	log AAL	6	0.943**
			Quadratic (c)				
PAM	= 3.00	−0.958	log AFE	−1.06	(log AFE)	6	0.831**
	= 3.18	−0.514	log TA	−2.04	(log TA)	6	0.964**
	= 0.64	−8.24	log AAL	−6.64	(log AAL)	6	0.920**
	= 0.98	2.02	log ESA	−0.455	(log ESA)	6	0.951**
	= −3.38	5.43	log TSA	−1.13	(log TSA)	6	0.968**
	= −0.55	3.94	log PCL	−1.03	(log PCL)	6	0.976**

+PAM = P-adsorption maximum; OC = organic carbon; TSA = total surface area; ESA = external surface area; AAL = amorphous aluminum; TA = total amorphous material; AFE = amorphous Fe; and PCL = percent clay; * and ** indicate significant at the 0.05 and 0.01 levels, respectively; n = number of observations.

The results of this study indicate that even in slightly acid to neutral surface horizons of soils with slightly basic subsurface horizons, amorphous Fe and Al still account for most of the P-sorption. The interaction of clay and amorphous Fe, Al and Si may produce a complex gel as reported by Mattson et al. (1950). This complex gel which is a site for P-fixation is reported to consist of hydrated Fe0 associated with small amounts of Al_20_3, organic matter and $Si(OH)_4$. The high correlation with external surface area is due to the clay content. Alternatively, high amorphous Fe and Al with large surface areas may be reflected in this correlation.

Most of the northern Cameroon soils under study are subjected to periodic flooding and, hence, recurrent reducing and oxidizing environments. Morphological, and microfabric analysis (Yerima, 1986) and the amount of amorphous Fe (Table 1) substantiate this process. Upon oxidation iron precipitates and probably forms a highly hydrated, amorphous solid phase with structural Si and Al which are released upon Fe reduction.

McCallister and Logan (1978) observed that Fe in Fe-substituted clay minerals is predominantly in the +3 oxidation state. Exposure to a redox potential as low as +100 mv at pH 7 could reduce Fe^{+3} to Fe^{+2} (Gotoh and Patrick, 1974), resulting in a change in ionic radius of the Fe, an increase in the layer charge, and a partial decomposition of the mineral. Since waterlogging conditions are seasonal the amorphous material does not have enough time to revert to crystalline forms; this may favor the formation of a complex gel with organic matter, Al and $Si(OH)_4$ as postulated by Mattson et al. (1950). The large surface area and strong bonding energy associated with amorphous material would then constitute the strong P-fixation sites.

About 83% and 96% of the variance in P adsorption maximum can be accounted for by amorphous Fe and Al, respectively (Table 4c). This study indicates that Al is more reactive in P-sorption for these Vertisols and associated soils than Fe. This finding is consistent with similar observations by other investigators (Taylor and Gurney, 1965; Hsu, 1965; Udo and Uzu, 1972) for more weathered soils.

There was no correlation between pH and PAM. Reports by other investigators (Udo and Uzu, 1972) showed a high negative correlation between P-adsorption and pH. The former authors attributed this phenomenon to the negative strong correlation between pH and exchangeable Al. The pH of the soils in this study were 5.7 or greater (Table 1) so little exchangable Al would be expected.

The low correlation of P-adsorption with organic carbon is consistent with findings by Udo and Uzu (1972) and Saunders (1965). The results are, however, inconsistent with observations by Harter (1969) who envisaged organic matter as providing a major site for P-sorption.

Use of the Two-Surface Langmuir

One of the assumptions for using the Langmuir equation as an adsorption model is the linear graphical plot of C/Pa versus C. If the bonding energy of adsorption sites on the soil surface are almost equal, the plot should give a straight line and, hence conform to the uniform surface adsorption model (Holford et al., 1974; Syers et al., 1973). The plots of C/Pa versus C for selected

soils (Fig. 3) show that the relation is curvilinear. This is consistent with studies by Bache and Williams (1971) and Holford et al. (1974) who also observed a curvilinear relationship.

In view of the above result it is apparent that in a heterogeneous soil system, sorption sites have different bonding energies. Hence, the two-surface Langmuir adsorption equation (2) better describes the sorption phenomena and will also be used to compare results with those obtained using the basic Langmuir equation.

Data plotted in Fig. 3 indicate that the line joining the first points is much steeper than the line fitted to all the seven points. Though the first part of the isotherm is linear, the full isotherm is curvilinear confirming that sorption is occurring on more than one type of surface. However, if sorption data in the <100 μg P/ml range are omitted, the linearity of the transformed data would be much higher. Hence, the goodness of fit for the uniform surface is largely dependent on the number and distribution of data points used in the P-fixation studies (Holford et al., 1974).

Use of the two-surface equation increased the total adsorption maxima by about 50 to 100% compared to the basic Langmuir equation (Table 5). The exception was the phosphate absorption maximum for the calcareous Lam soil which was increased nearly 4-fold. In all the soils, except the Lam soil, PAM″ was about 3 to 4 times greater than PAM′ while K′ was about 10 to 65 times greater than K″.

Table 5. Observed and predicted P-adsorption maxima and derived bonding energies for the uniform-surface and two-surface Langmuir equations for some northern Cameroon soils.

	Uniform Surface		Two Surface				
Soil Series	PAM μg/g	$K \times 10^3$ ml/μg	PAM′ μg/g	$K' x 10^3$ ml/μg	PAM″ μg/g	$K'' \times 10^3$ ml/μg	TPAM μg/g
Andirni	1282	25.9	546	184	2041	4.4	2587
Louba Louba	1695	60.1	756	571	2183	11.4	2939
Lam	2564	11.4	382	437	9510	1.1	9892
Laf	1266	31.4	399	570	1612	9.0	2011
Maga	1667	40.1	505	158	2024	16.0	2529
Mora	160	95.5	—	—	—	—	—
Kousserie	1031	10.8	246	161	1538	4.0	1784

PAM = P-adsorption maximum for the Basic Langmuir equation; PAM′ and PAM″ are the P-adsorption maxima for the high energy and low energy sites and K′ and K″ are the bonding energies for the high and low energy sites, respectively; TPAM is total adsorption maximum.

Regression equations relating PAM', PAM" and total P adsorption maxima (PAM′ + PAM″ = TPAM) to the log of various soil physical properties are presented in Table 6. Percent clay, total surface area, and amorphous aluminum were most highly correlated with P-sorption in the PAM′ (high energy sites). Percent clay, pH, amorphous aluminum and external surface area were most significant in predicting P-fixation for the low energy sites (PAM″) (Table 6). Amorphous aluminum was more highly correlated with PAM′; amorphous Fe was more highly correlated with PAM″ (Table 6).

Table 6. Simple linear regression equations relating P adsorption maximum of the high energy sites (PAM′), low energy sites (PAM″), and total adsorption maxima (PAM′ + PAM″ = TPAM) to some physical and chemical properties using the Langmuir two-surface equation.

Dependent variable	Intercept	Coefficient	Variable	n	r^2a
		Linear (a)			
PAM′	= 0.554	1.25	log PCL	6	0.923*
	= 0.083	1.13	log TSA	6	0.900**
	= 3.65	1.54	log AAL	6	0.852*
	= 2.87	0.884	log TA	6	0.816
	= 0.459	1.24	log ESA	6	0.545
	= 3.98	−0.211	pH	6	0.489
	= 2.89	0.413	log AFE	6	0.384
	= 2.86	1.29	log OC	6	0.206
PAM″	= 2.48	0.471	log PCL	6	0.932**
	= 3.35	0.353	log TA	6	0.972**
	= 3.87	−0.096	pH	6	0.867*
	= 3.37	0.193	log AFE	6	0.780*
	= 2.34	0.522	log ESA	6	0.776
	= 3.57	0.463	log AAL	6	0.434

Dependent variable	Intercept	Coeff. (X1)	Variable (X1)	Coeff. (X2)	Variable (X2)	n	R^2a
			Quadratic (b)				
TPAM	= 4.46	0.331	log TA	−0.256	(log TA)	6	0.954
	= 2.41	0.513	log PCL	0.032	(log PCL)	6	0.955
	= 3.62	0.774	log AFE	0.440	(log AFE)	6	0.731
	= 8.09	−4.86	log TSA	1.22	(log TSA)	6	0.706
	= −5.03	8.79	log ESA	−2.28	(log TSA)	6	0.655
	= 4.14	1.68	log AAL	0.744	(log AAL)	6	0.429

Where PCL + percent clay; TSA = total surface area; AAL = amorphous aluminum; AFE = amorphous FE; OC = organic carbon; ESA = external surface area; TA = total amorphous material.

* and ** indicate significant at 0.05 and 0.01 levels, respectively.

n = number of observations.

DISCUSSION

The linear relationship observed with total adsorption maxima of the two-surface Langmuir and different soil properties confirms observations by Holford et al. (1974) and Mattingly (1975) that phosphate is adsorbed on two types of surfaces with different bonding energies. The adsorption maximum calculated from the two-surface (PAM′ + PAM″) Langmuir equation was 50 to 100% higher than that calculated using the basic Langmuir equation (PAM) (Table 5). These values are close to the 48% range reported by Holford et al. (1974) for Australian soils but much lower than the 240% reported by Gunary (1970) using empirical equations.

The erratic adsorption phenomenon and the marked variation observed for duplicates in the >100 μg P/ml solution equilibrium, for the carbonate-rich Lam soil (Fig. 3), are probably symptomatic of a greater magnitude of both precipitation and adsorption phenomena. Previous studies (Holford et al., 1974) have shown that precipitation causes marked variation between du-

plicate determinations, attributable to variation in the rate of crystallization (Cole et al., 1953). Cole et al. (1953) concluded that P adsorption followed a Langmuir isotherm up to 9 mg P/l at which concentration there was evidence of precipitation.

When these soils were equilibrated with 10-500 μg P/ml the high energy sites were more highly correlated with amorphous aluminum and the low energy sites were more correlated with amorphous iron. Since these soils have high P-sorption capacities and very low amounts of available P, when they are equilibrated with low P concentations the sorption data fits the basic Langmuir equation.

Phosphorus sorbed on the high energy sites are much more tightly held than those on the low energy sites. Equilibration of these slightly acid soils with increasing amounts of P beyond 50 μg P/ml will lead to formation of aluminum phosphate and iron phosphate and obviate detection of the high energy sites.

This study indicates that when the basic Langmuir equation is used, correlation of soil properties with the P-sorption maxima is better described by use of a quadratic (power series models) relationship because it corrects for curvilinearity. However, because the two-surface Langmuir equation takes account of the different bonding energies and is split into a high energy and low energy phase which are linear, two simple linear regression relationships provide the best model.

MANAGEMENT IMPLICATIONS

The primary objectives of this study were to address the effects of nutrient P on forest regeneration (Yerima, 1986). The soil solution P concentration required for trees is greater than that required for food crops. One approach is to utilize PAM to evaluate the amount of P to be applied to retain a given concentration of P in solution for plant growth. The PAM′ (P on high energy sites) was closely related to the amount of P required to obtain 0.7 μg P/ml in equilibrium soil solution. This can be considered as desirable since precipitation and leaching will be reduced when P is held on the high energy sites. Though expensive, high initial P application on forest plantations will give residual effects and reduce annual fertilizer applications.

Fertilizer P application is needed to supplement naturally occurring P in most soils to produce economic yields for many crops. Soil test methods, including the NH_4HCO_3-DTPA test, have been developed to measure the pool of available inorganic P to plants in alkaline soils. The soils of northern Cameroon are low in measured available P and supplemental P is needed to insure growth of trees (Yerima, 1986). An additional source of P for plants that is not measured by NH_4HCO_3-DTPA extractant is the organic fraction of the A horizon of these soils which is relatively high in this form of P. Although data are unavailable for northern Cameroon, Stewart and Sharpley (1987) found that the annual amount of organic P mineralized during spring and early summer in a Texas Vertisol (Houston Black clay) was related to the amount of organic P present and ranged from 14 to 26% of the total organic P. The organic P in Vertisols of northern Cameroon ranged from 15.5 to 34.8% of the total P in

the A horizon. If organic P mineralization is comparable to Texas Vertisols, 15 to 53 kg P ha^{-1} per year could potentially be derived from the organic fraction. In general, the amount of organic P mineralized increases significantly if the soil has not been fertilized and is in permanent pasture (Stewart and Sharpley, 1987). The absolute amount of P mineralized in temperate region soils appears to be fairly consistent (Grove, 1983; Stewart and Sharpley, 1987) at a level of 4.0 to 6.0 kg P ha^{-1} per year. Differences due to soil type, cropping system, temperature and moisture are to be expected.

Fertilization and consideration of the organic P fraction of the Vertisols of northern Cameroon appear to be options available for long-term management of these soils. Fertilizer requirements of these soils in the long-term may require more extensive evaluation of both the inorganic and the organic P pools. Careful management of the organic matter pool could significantly impact the quantity of fertilizer P needed for reforestation of these soil resources. Soil test methods which include the total amount of P extracted (organic + inorganic) may give more reliable estimates of available P when determined on a site specific basis. For example, Bowman and Cole (1978) used a modification of the Olsen bicarbonate method (Olsen et al., 1954) to measure the total amount of P extracted. They concluded that it appears appropriate to use both organic and inorganic P extracted (rather than just inorganic P) as a better indicator of potentially available P, especially for soils determined to be deficient or borderline deficient using the traditional $NaHCO_3$ extraction method.

Vertisols have historically been difficult soils to manage for intensive agricultural production. The high smectite content and shrink-swell characteristics present difficulties in tilling and managing these soils even with modern equipment and techniques. When permanent reforestation is practiced on Vertisols, physical constraints to root growth may be as limiting as the chemical properties. The high shrink-swell properties, and shear strength of these soils may be a major constraint to reforestation efforts.

SUMMARY

Total, organic and NH_4HCO_3-DTPA extractable forms of P were determined and P-sorption studies were performed on six northern Cameroon Vertisols and one Alfisol. Four of the Vertisols were developed from Quaternary lacustrine sediments and are seasonally flooded, while two are developed from Precambrian schist in upland positions. The Alfisol was developed on an upland position from Precambrian granite. Ranges for total and organic P were 116-590 and 5-102 $\mu g/g$, respectively. The NH_4HCO_3-DTPA extractable P ranged from 0.1-2.1 $\mu g/g$ and was higher in the surface horizons of the seasonally flooded soils but low in $CaCO_3$-rich schist derived soils.

Phosphorus-sorption studies indicated an initial fast reaction followed by a slow kinetic process. Phosphorus sorption and phosphorus-sorption maxima (PAM) were correlated with surface area, clay content and oxalate extractable Fe and Al contents. Basic Langmuir plots indicated heterogeneous P-sorption sites characterized by a high energy (PAM′) and a low energy (PAM″) phase. It was necessary to exceed 50 μg P/ml in equilibrium solution to detect the

low energy phase. When the basic Langmuir equation was used to calculate PAM, the relationship of P-sorption maxima versus physico-chemical properties was best expressed by quadratic equations. When the two-surface Langmuir was used, simple linear equations adequately explained relationships between P-sorption maxima and soil properties due to correction for curvilinearity. Amorphous Al was more highly correlated with high energy sorption sites and amorphous Fe was more highly correlated with the low energy sorption sites when a 10-500 μg P/ml range in equilibrating solution was used.

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Chapter 10

CONSERVATION TECHNIQUES FOR VERTISOLS

P. W. Unger and B. A. Stewart

INTRODUCTION

Most of the world's soils, including Vertisols, are subject to erosion by water and wind. The high susceptibility to erosion by water results from the Vertisols' characteristically low infiltration rates and, often, their occurrence on sloping soils. Although Vertisols cover only about 1.8% of the world's land surface (Donahue et al., 1977), they are highly important for the production of the world's food and fiber and need to be conserved to sustain that production. Coupled with this need, in many cases, is an urgent need to conserve water because Vertisols often occur where inadequate precipitation limits crop yields.

The effectiveness of permanent vegetative covers for controlling erosion is well known, but permanent covers of grasses and trees usually are not compatible with crop production. Consequently, alternate conservation practices must be employed. A practice that can be as effective as a permanent cover of grasses or trees is conservation tillage, which retains a cover of crop residues on soil during critical erosion periods. A complete cover of residues gives the most protection, but lesser amounts provide enough protection so that annual erosion does not exceed the tolerable level for many soils. Approximate amounts needed are given in Table 1.

The residue amounts shown in Table 1 are relatively low. However, such amounts often are not produced by rainfed crops in many areas, and residues of crops such as cotton (*Gossypium hirsutum L.*) provide little protection against erosion. In addition, residues in some countries often are used for fuel or animal feed. When crop residues are not available, for whatever the reason, then alternate measures must be employed. In this report, we discuss conservation tillage methods for situations where crop residues are available, clean

Table 1. Approximate amounts of residue needed to maintain annual erosion at below a tolerable level of 11.2 Mg ha^{-1} (5 tons/acre) on a clay† soil (from Anderson, 1968; Fenster, 1973).

Residue condition	Residue required to control erosion by Water	Wind
	—— Mg ha-1 ——	
Wheat residue		
Flattened	2.10	1.80
Standing	—	0.90
Growing wheat		
Flattened	—	0.93
Standing	—	1.10
Sorghum residue		
Flattened	—	5.30
Standing	—	3.70

†Clay with 25% nonerodible fractions.

tillage for situations where residues are limited or are incorporated by tillage, and support practices that provide additional protection against soil and water losses.

In our discussion, we have relied on data obtained on Vertisols or Vertic intergrades when such data were available. Unfortunately, that was not always possible. We then relied on data from other soils to illustrate expected results because we believe that the same principles apply to Vertisols in many cases. However, we caution readers that actual results may be different because of differences in soil minerals, clay contents, drainage, structure, etc.

TILLAGE METHODS

Conservation Tillage

A commonly accepted definition of conservation tillage is any tillage system that leaves at least 30% of the soil surface covered with residues after a crop is planted. This definition implies that a similar or greater amount of residues will be present at all times during the interval between crops. Another definition for conservation tillage is "any tillage sequence that reduces loss of soil or water relative to conventional tillage; often a form of noninversion tillage that retains protective amounts of residue mulch on the surface" (SCSA, 1982). Although the second definition does not require that surface residues be present, both definitions recognize the importance of surface residues for reducing soil and water losses. We will use the more restrictive definition, namely, that surface residues be a part of a conservation tillage system. When residues cover about 30% of the soil surface, soil erosion is reduced about 50% as compared to that with no residues on the surface (Moldenhauer et al., 1983). The following are types of conservation tillage methods, most of which have been the subject of considerable research.

Stubble mulch.

Stubble mulch tillage is accomplished with implements (sweeps or blades) that undercut the soil surface, thereby retaining most crop residues on the surface. Stubble mulch tillage can be performed also with a chisel plow, but a rotary rodweeder may be needed to improve weed control (Allen and Fenster, 1986). The rodweeder has a rotating bar that is operated slightly below (3-5 cm) the surface.

Stubble mulch tillage was developed to control wind erosion in the Great Plains, but it also reduces water erosion and enhances water conservation. Because stubble mulch implements reduce surface residues only about 10% for each operation, adequate residues usually are maintained to control erosion, provided sufficient amounts were available initially.

One disadvantage of stubble mulch tillage is inadequate weed control when tillage is performed while the soil is moist or when precipitation occurs soon after tillage. Some grassy weeds may be especially difficult to control. To improve weed control and to firm soil before planting, shallow tillage with a rodweeder often is used in a stubble mulch system. Shallow tillage also reduces seed zone drying and improves hoe-drill seeding into moist soil in the U.S. Great Plains.

Stubble mulch and oneway disk (clean) tillage were compared by Johnson and Davis (1972) for winter wheat (*Triticum aestivum L.*) on Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) at Bushland, Texas, where annual precipitation averages 470 mm. The soil is a Mollisol but has about 30 and 45% clay in the surface and subsurface horizons, respectively, and a relatively high shrink-swell potential. Therefore, it is similar to a Vertisol. Although water storage and yield increases were small (Table 2), the stubble mulch system provided protection against erosion, mainly by wind. Water erosion is not a major problem on Pullman soils (personal communication, O. R. Jones, Bushland, Texas).

Table 2. Average plant available soil water contents at time of planting and grain yields for a long-term (1942-1969) study for rainfed winter wheat at Bushland, Texas (from Johnson and Davis, 1972).

Cropping system and tillage method	Soil water content	Grain yield
	mm	$Mg\,ha^{-1}$
Continuous wheat		
Oneway disk	91†	0.58†
Stubble mulch	103	0.69
Wheat-fallow		
Oneway disk	128‡	0.93‡
Stubble mulch	154	1.06
Delayed stubble mulch§	144	1.03

†Differences due to disk and stubble mulch tillage treatments are significant at the 1% level.

‡Differences between disk and stubble mulch or delayed stubble mulch tillage treatments are significant at the 1% and 5% levels, respectively.

§Tillage delayed until weeds needed control in the spring (about 10 months after wheat harvest).

Where weed control is difficult with stubble mulch tillage, improved control can be achieved through use of herbicides that replace some tillage operations. Wicks and Smika (1973) in Nebraska found that no-tillage (herbicide treated) plots on a Holdrege silt loam soil (fine-silty, mixed, mesic Typic Fragiboralf) had the least weeds, most stored soil water, most surface residues, and highest wheat grain yields. Yields averaged 2.69, 2.89, and 3.16 Mg ha^{-1} with clean, stubble mulch, and no-tillage, respectively. In another study, sorghum [*Sorghum bicolor (L.) Moench*] grain yields averaged 3.20 Mg/ha^{-1} with stubble mulch tillage and 4.58 Mg/ha^{-1} with a combination tillage-herbicide treatment (Fenster, 1977). The tillage-herbicide treatment may be especially suited to Vertisols, which become very sticky when wet and, hence, difficult to plow for timely weed control.

Disk.

Disk-type implements bury from 30 to 70% of surface residues during each operation, depending on the implement used and how it is operated (Fenster, 1977). Disk-type implements provide good weed control, but should be used as conservation tillage implements only if sufficient residues are retained on the soil surface. Where residue production is low and the potential for erosion is high, disk-type implements should not be used. In addition to greatly reducing surface residues, disk implements pulverize soils and reduce surface roughness. Pulverized, smooth-surfaced soils are more susceptible to erosion, and water infiltration is lower than into residue-covered or rough-surfaced soils.

Ridge-plant.

Ridge planting is a once-over tillage-planting operation. The planter units are operated on ridges made by cultivation of the previous crop or after crop harvest. At planting, till-plant units remove the ridge tops with sweeps, and old stalks and root clumps are moved into the inter-row area. Seed is planted in the cleared area of the old ridge. Ridges are reformed with rolling or disk-hiller cultivators after crop establishment (Griffith et al., 1977). Although developed for corn (*Zea mays L.*), the system is suitable for other row crops also. Conservation benefits result from the soil being covered with residues or a growing crop during most of the year. Additional runoff control benefits occur if the ridges are on a slight grade or on the contour. In high rainfall areas, ridge planting benefits poorly-drained Vertisols because the ridges usually are drier and better aerated than furrows or land that is managed in a flat condition.

No-tillage.

No-tillage (or zero tillage or slot planting) has been acclaimed as a highly effective conservation practice. No-tillage requires no seedbed preparation other than opening soil for seed placement, usually with a coulter operated ahead of a planting unit equipped with disk or chisel openers (Mannering and Fenster, 1983). Similar equipment may be used to apply fertilizer.

With no-tillage, weeds are controlled with herbicides. Consequently, all crop residues are maintained on the soil surface, which improves erosion control and enhances water conservation through improved infiltration and reduced evaporation. For no-tillage to be effective, adequate residues must be present. No-tillage is not and cannot be expected to be effective on seriously degraded soils or where residue amounts are low. Where residue amounts ranged from about 1.5 to 2.5 Mg ha^{-1} and weeds were controlled with herbicides, water storage and crop yields were similar to those with stubble mulch tillage (Wiese and Army, 1958; Wiese et al., 1960). When more residues were present, Unger and Wiese (1979) obtained greater water storage and higher sorghum grain yields with no-tillage than with other treatments on the Pullman soil at Bushland, Texas (Table 3). Higher infiltration and lower evaporation undoubtedly were responsible for greater water conservation with no-tillage. In another study at Bushland, Texas (Unger, 1984), water storage during fallow after irrigated wheat and yields of grain sorghum planted after fallow averaged highest with no-tillage (Table 4). The treatments applied during fal-

Table 3. Effect of tillage method on average soil water storage during fallow after wheat, sorghum grain yield, and grain yield water use efficiency (WUE) for the sorghum crop in an irrigated winter wheat-fallow-dryland grain sorghum cropping system at Bushland, Texas, 1973 to 1977 (from Unger and Wiese, 1979).

Tillage method	Precipitation: Fallow	Precipitation: Growing season	Water storage†	Grain yield	WUE‡
	mm	mm	%	Mg ha^{-1}	kg m^{-1}
No-tillage	348	264	35 a	3.14 a	0.89 a
Sweep	348	264	23 b	2.50 b	0.77 b
Disk	348	264	15 c	1.93 c	0.66 c

†Based on fallow period precipitation stored as soil water.

‡Based on total water use (precipitation plus soil water extraction) during the sorghum growing season.

Table 4. Effect of tillage method on average soil water storage during fallow after irrigated winter wheat and on subsequent rainfed grain sorghum yields at Bushland, Texas, 1978 to 1983 (from Unger, 1984).

Tillage treatment	Precipitation: Fallow	Precipitation: Growing season	Water storage†	Grain yield
	mm	mm	%	Mg ha^{-1}
Moldboard	316	301	29 b‡	2.56 bc‡
Disk	316	301	34 ab	2.37 cd
Rotary	316	301	27 b	2.19 d
Sweep	316	301	36ab	2.77 b
No-tillage	316	301	45 a	3.34 a

†Based on fallow period precipitation stored as soil water.

‡Column values followed by the same letter or letters are not significantly different at the 5% level based on the Duncan multiple range test.

low after wheat had no residual effects on yields of sunflower (*Helianthus annuus L.*) or wheat that followed the intervening sorghum crop.

On a Mollisol (Austin series — fine-silty, carbonatic, thermic Entic Haplustoll) at Temple, Texas, where annual precipitation is 840 mm, Gerik and Morrison (1984) obtained similar soil water storage and sorghum grain yields by using no- and conventional-tillage treatments. However, no-tillage has potential for the region because production costs are lower and it permits growing sorghum in narrow rows, which has potential for higher yields. Narrow-row production is not possible with clean tillage where sorghum must be cultivated to control weeds. The effect on erosion was not reported, but surface residues with no-tillage undoubtedly greatly reduced erosion on the highly erosive soil. Also on the same soil, wheat yields in a 3-year study with wide beds were not significantly different in two years, but were significantly lower with no-tillage in a droughty year because of less tillering (Gerik and Morrison, 1985).

Jones and Benyamini (1984) at Bushland, Texas, applied water with a rainfall simulator to plots on Pullman soil that were in a winter wheat-fallow-grain sorghum-fallow system. No-tillage and stubble mulch tillage were used for weed control. During fallow after wheat and for sorghum with full canopy, infiltration rates were similar with both treatments. During fallow after sorghum, infiltration decreased much more rapidly with no-tillage because of the low amount of residues present. However, runoff during a 110-mm natural rainstorm (June 1984) was 81 and 85 mm from the 2.2-ha no- and stubble mulch tillage watersheds, respectively. Soil loss with stubble mulch tillage was 6.56 Mg ha^{-1}, but only 2.15 Mg ha^{-1} with no-tillage. Soil loss was 0.24 Mg ha^{-1} and runoff was 38 mm from no-tillage plots in fallow after wheat during the storm.

The vast potential of no-tillage practices for controlling erosion by water on sloping watersheds is illustrated by data (Table 5) for a storm in Ohio that had an expected recurrence frequency of over 100 years (Harrold and Edwards, 1972). The soil series was not given. Corn was grown on all watersheds. Rainfall and slopes were similar for clean-tilled watersheds, but runoff was only 52% and soil loss was only 14% from the contour-row watershed as compared to that from the sloping-row watershed. On the no-tillage watershed, rainfall was slightly lower, and about 50% of the water was lost as runoff. However, soil loss with no-tillage was only about 0.1 and 1.0% as much as that from

Table 5. Runoff and soil losses from watersheds planted to corn at Coshocton, Ohio, during a severe rainstorm on July 5, 1969 (from Harrold and Edwards, 1972).

Tillage	Slope	Rainfall	Runoff	Soil loss
	%	mm	mm	Mg ha^{-1}
Plowed, clean-tilled sloping rows	6.6	140	112	50.7
Plowed, clean-tilled, contour rows	5.8	140	58	7.2
No-tillage, contour rows	20.7	129	64	0.1

sloping- and contour-row clean-tillage watersheds, respectively, even though the slope was much steeper on the no-tillage watershed.

Freebairn et al. (1985) studied the effects of no-tillage residue management on a Vertisol in Australia. Runoff, soil loss, and yields were determined from plots that had slopes of 5 to 7%. Tillage treatments were bare fallow (clean tillage), residues incorporated with disks, stubble mulch tillage, and no-tillage. With more than 24% of the surface covered with residues, both runoff and soil loss were reduced as compared with clean tillage. Soil erosion with no-tillage averaged 1.0 Mg ha^{-1} per year as compared to 30 to 70 Mg ha^{-1} per year with clean tillage. Winter crops with reduced (stubble mulch) and no-tillage yielded 12% more than with clean tillage. In another study on a Vertisol in Australia, Marston and Perrins (1981) obtained significantly less runoff and soil loss from no-tillage plots than from plots where the crop residues were incorporated.

In India, water infiltration rate into a Vertisol was greater where a compost was added or where sorghum straw or cassava (*Manihot sp.*) leaves were allowed to decompose in place than where no compost or leaves were available (Table 6). The improved infiltration resulted from the materials on the surface and from improved soil aggregation (Venkateswarlu, 1984). Decaying surface residues undoubtedly contribute greatly to the improved infiltration with no-tillage systems, but the dissipation of raindrop energy, which minimizes soil detachment and surface sealing, and the impedance to surface lateral water flow, which allows more time for infiltration, also are important functions of surface residues in no-tillage systems with respect to water infiltration. Because of less runoff, soil erosion by water is reduced also.

No-tillage also is highly effective for controlling wind erosion, as illustrated by data in Table 7 for a sandy soil. Losses from a Vertisol would be different, but wind erosion does occur on bare, smooth, unprotected Vertisols. In such cases, surface residues would reduce wind erosion and protect the crops.

Paraplow.

The paraplow is an implement that loosens the soil, but does not invert it, and retains most crop residues on the soil surface. In Iowa, surface residues after planting averaged 75% with the paraplow, 83% with no-tillage, and 12%

Table 6. Effect of *in situ* decomposition of different materials on soil aggregation and infiltration (from Venkateswarlu, 1984).

Treatment	Soil aggregation	Water infiltration rate into disturbed soil
	MWD	cm/hr
Control	0.11	2.59
Compost	0.11	4.39
Sorghum straw	0.16	4.75
Cassava leaves	0.38	8.10

MWD = Mean weight diameter (mm).

Table 7. Effect of tillage system on wind erosion with corn stalks on land in Ohio (from Woodruff, 1972).

Tillage	Surface residues	Soil loss
	Mg ha^{-1}	
Experiment I		
Fall plow	0.28	26.1
Spring plow	0.12	8.5
No-tillage	5.60	1.2
Experiment II		
Plow, normal residues	0.14	3.5
Disk, normal residues	0.54	5.1
Disk, double residues	1.76	0.8
No-tillage, residues removed	0	3.0
No-tillage, normal residues	1.82	0.6
No-tillage, double residues	2.85	0.5

with moldboard plowing (Erbach et al., 1984). The soils were Webster silty clay loam (Typic Haplaquoll) and Haig silt loam (Typic Argiaquoll). Soil water contents were similar, but corn yields were 4.4 and 4.9 Mg ha^{-1} with the no-tillage and paraplow treatments, respectively, as compared with 5.6 Mg ha^{-1} with moldboard plowing. In England (Davies et al., 1982) and the U.S.A. (personal communication, John F. Dougherty, Howard Rotovator Co., Inc., Muscoda, Wisconsin), runoff was lower with the paraplow than with no-tillage or plowing treatments. Reducing runoff reduces the potential for erosion. From limited data available, it appears that paraplowing has potential for conserving soil and water on dense, high clay soils such as Vertisols by maintaining surface residues and favorable infiltration rates.

Clean Tillage

When conservation tillage is not used, either by choice or because of inadequate crop residues, then other practices must be relied upon to conserve resources. Wind erosion on clean-tilled Vertisols usually can be controlled by any tillage that produces an adequately rough, cloddy surface. Secondary tillage operations and weathering (rainfall, drying, etc.) may decrease surface ridges and cloddiness to the point that they no longer afford protection against the wind. Unless soil is pulverized, any operation to ridge it or increase its surface cloddiness usually is adequate as an emergency measure to control wind erosion on a Vertisol.

To control water erosion on Vertisols where clean tillage is used, infiltration must be increased or water must be conveyed off the land at nonerosive velocities. To achieve this, soil ridging or tillage to roughen the surface often is used in conjunction with graded furrows, contouring, furrow diking, terracing, or other practices.

The influence of tillage *per se* on runoff and, consequently, on water erosion is related to the stability of surface soil aggregates and the roughness, surface detention storage, and pore space that result from tillage with different

implements. To maintain high infiltration rates, water-stable surface aggregates are desirable. These normally result from maintaining organic materials at or near the soil surface. Low-stability soils are readily dispersed by water, which causes surface sealing and increases runoff and erosion.

When precipitation rates exceed infiltration rates, temporary surface storage of water can reduce runoff and aid in controlling erosion. Ridge-forming tillage on the contour is a proven conservation practice (Dickson et al., 1940; Fisher and Burnett, 1953; Harrold and Edwards 1972). Runoff also may be eliminated by furrow diking of gently sloping land (Clark and Jones, 1981). In that study, all water from a 114-mm rainstorm during a 24-hour period was retained on the Pullman soil at Bushland, Texas.

In addition to lister tillage, implements such as moldboard plows, sweep plows, disks, chisels, rotary tillers, cultivators, etc. affect soil pore space and surface roughness and, therefore, runoff and erosion. Burwell et al. (1966) evaluated effects of porosity and roughness resulting from tillage on infiltration of simulated rainfall on Barnes loam (Udic Haploboroll) (Table 8). Cumulative infiltration approached plow-layer total pore space and surface retention volumes for the plow treatment before runoff started. Infiltration exceeded those volumes before 25 mm of runoff occurred. Storage volumes were not filled for the untilled, plow-disk-harrow, cultivated, and rotovated treatments, even though 50 mm of runoff occurred. Smoother surfaces with treatments other than plowing apparently resulted in more rapid soil dispersion and surface sealing, which reduced infiltration.

One practice that involves clean tillage but which has considerable potential for controlling erosion is the plow-plant system, for which plowing is delayed until 12 to 24 hours before planting. Consequently, the soil remains residue covered for a major part of the erosion period. Planting may be in tractor or planter wheel tracks (Griffith et al., 1977). Variations of this system are disking and planting; fall chiseling, then disking, cultivating, or rotary tilling before planting; or rotary tillage (strip or full width) and planting (Griffith et al., 1977).

Table 8. Effect of tillage-induced plow layer porosity and surface roughness on cumulative infiltration of simulated rainfall (from Burwell et al., 1966).

	Potential water storage volume due to		Cumulative infiltration§ to		
Tillage treatment†	Pore space‡	Surface roughness	Initial runoff	25 mm runoff	50 mm runoff
	mm				
Untilled	81	8	9	21	24
Plow	137	50	171	217	230
Plow-disk-harrow	124	25	53	73	84
Cultivated	97	29	57	83	91
Rotovated	117	15	24	38	41

†Plowing and rotovating performed to a 15-cm depth; cultivating to a 7.5-cm depth on untilled soil.

‡Measured to tillage depth.

§Water applied at a 127-mm/hour rate.

SUPPORT PRACTICES

By using conservation tillage methods, especially no-tillage, lands that otherwise are highly susceptible to erosion can be safely cropped in many cases because of the protection afforded by surface residues. However, such lands are highly susceptible to erosion where clean-tillage methods are used; and, therefore, support practices must be used in conjunction with tillage to conserve soil and water. In this section, we discuss practices that can be used for that purpose. For this report, support practices are engineering-type practices and cultural practices (other than tillage) that aid in conserving soil and water resources.

Contouring

Contouring involves performing tillage and cultural operations along rows that are as level as practical. When lister tillage or ridge planting is done on the contour, the potential for erosion by surface water flow is greatly decreased (Stewart et al., 1975). Contouring provides almost complete protection against erosion from low- to moderate-intensity storms but little or none against intense storms that overtop and break the contoured ridges. In such cases, water conservation is reduced also. However, with lesser storms and proper use, contouring promotes uniform water storage on the entire field. With lister tillage, each ridge serves as a miniature level terrace and, thus, holds water on the land. Contouring has no direct value for controlling wind erosion unless the ridges increase surface roughness perpendicular to the wind direction.

Stripcropping

Stripcropping reduces water and wind erosion. For reducing water erosion, alternate protective and cropped strips are usually of equal width. Soil eroded from cropped areas is trapped in the protective strip. Stripcropping reduces soil losses from a field, but may not prevent movement within a field (Wischmeier and Smith, 1978).

Stripcropping is widely used for wind erosion control in the United States where fallow and cropped areas that are perpendicular to prevailing winds are alternated. On fallow areas, residues from small grain crops provide some protection against wind erosion by reducing field length in the direction of prevailing winds. In other areas, narrow strips of tall plants have given some control of wind erosion and conserved water (Hagen et al., 1972; Black and Siddoway, 1971).

Terraces

Terraces are constructed across the slope to conduct runoff at nonerosive velocities. If level, they retain water on fields until infiltration occurs, thus

making more water available to plants. Terraces usually are used in conjunction with waterways or underground outlets to safely dispose of excess water (ASAE, 1982). The effectiveness of terraces for conserving soil and water can be enhanced by the complementary practices of contouring, stripcropping, diking, and conservation tillage.

Maximum water retention for crop use is obtained with bench or conservation bench terraces; this requires land leveling. With bench terraces, the entire terrace interval is leveled and water is retained on the bench. Ridges are cropped or remain permanently vegetated. With conservation bench terraces, only a portion of the inter-terrace interval is leveled for concentration of runoff water, usually the lower one third or one half. Thus, costs for construction are less than for bench terraces. Bench, conservation bench, and minibench (narrow) terraces are effective for reducing erosion and increasing crop yields on slowly permeable soils in semiarid climates. Minibench terraces are designed to accommodate fixed-width equipment (only one- or two-equipment widths wide in the U.S.A.) (Hauser, 1968; Jones, 1981).

Graded terraces are constructed to reduce field slope and water flow velocities, which reduces erosion. The grade to the outlet may be uniform or variable. Level terraces are built in low rainfall areas to conserve water and to control erosion. Channel ends of level terraces often are blocked to retain runoff on the field.

Terrace outlets are classified as (a) blocked, where surface water is retained in the terrace channel; (b) grassed waterway, where water is drained into vegetated waterways; or (c) underground outlet, where water is removed from terrace channels by underground pipe. The latter outlets aid in erosion control and remove less land from production. Combinations of the various outlet systems may be used.

Diversions

Diversion terraces are individually designed channels and ridges across the slope that are used to protect field areas against runoff from unterraced areas, to divert water out of active gullies, and to protect farm improvements. Diversions often are used to prevent outside runoff from entering terraced fields.

Graded Furrows

In contrast to contour furrows, which minimize runoff and erosion, graded furrows convey runoff water from fields at nonerosive velocities. Each furrow functions as a small graded terrace. Although designed to remove excess water, graded furrows also conserve water. Runoff from graded-furrow and terraced watersheds on Houston Black clay (Udic Pellustert) was 187 and 236 mm, respectively, during a 32-month period at Temple, Texas (Richardson, 1973). Runoff was reduced with graded furrows because the water was more uniformly distributed over the entire field, which provided more time and area for infiltration.

Furrow Dikes

Furrow dikes (tied ridges) can effectively conserve water by retaining potential runoff on field areas until it infiltrates. With this practice, small earthen dikes are constructed between cropped ridges that are formed with a lister (bedder). The dikes are built across the furrow at 1- to 4-m intervals, depending on slope and available equipment. Furrow diking increased sorghum yields an average of 1.46 Mg ha^{-1} on Sherm silty clay loam (Torrertic Paleustoll) at Etter, Texas, for 1980 and 1981 but only 0.23 Mg ha^{-1} on Pullman clay loam at Bushland, Texas, from 1975-79 as compared with open furrows (Clark and Jones, 1981).

Limited Irrigation-Dryland Farming System

Stewart et al. (1983) developed a limited irrigation-dryland (LID) farming system to maximize the conjunctive use of growing season rainfall, which varies for any given year, with a limited supply of irrigation water, which is fixed for a given year. The unique feature of the system is the flexible adjustment during the crop growing season, which allows more land to be irrigated during above-average rainfall years than during dry years. Risk is low with the system, and response is good in favorable rainfall years.

The LID system concept is illustrated in Fig 1. A 600-m long graded-furrow field on 0.3 to 0.4% slope was divided into three water management sections. The upper half was managed as "fully irrigated", the next one-fourth as a "tailwater runoff" section that utilized runoff from the fully irrigated section,

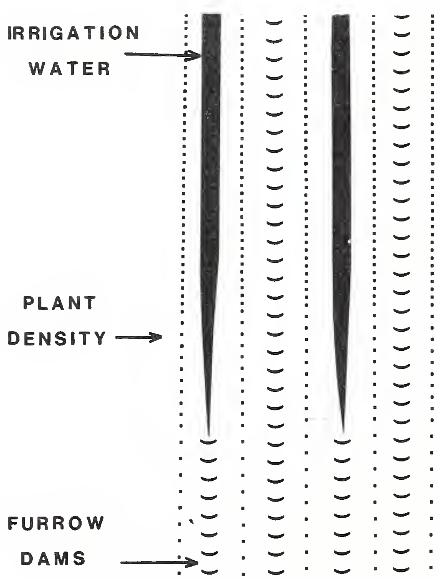

Fig. 1. Schematic drawing of the Limited Irrigation-Dryland (LID) System.

and the lower one-fourth as a "dryland" section capable of receiving and utilizing any runoff resulting from either irrigation or rainfall on the wetter, fully irrigated and tailwater runoff sections. Plant densities were reduced down the field to moderate stress severity because irrigation water was decreased as the length of the field increased. Furrow dikes were placed about every 4 m throughout the length of the field. Dikes in furrows to be irrigated were notched to insure that irrigation water moved over the dikes and down the furrows, rather than across the beds. Alternate furrows were irrigated. The remaining dikes on the lower part of the field and those in the nonirrigated furrows prevented rainfall runoff. A predetermined amount of irrigation water was applied at regular time intervals. The extent to which the field was irrigated depended on the rainfall received—the wetter the year, the greater the advance of a fixed amount of water down the field. The objective was to prevent or minimize water from rainfall or irrigation from leaving the field. More recent studies with the LID system have utilized a medium seeding rate throughout the field and dikes only in alternate furrows that are not used for irrigation. These changes made the system somewhat easier to manage, and the benefits were similar.

The system was field tested on Pullman clay loam at Bushland, Texas, in 1979, 1980, and 1981. The results are given in Table 9. Runoff was greatly reduced with all treatments as compared with that for the fully irrigated treatment. Grain yields increased in response to the amount of irrigation applied and closely paralleled evapotranspiration. Consequently, water use efficiency (WUE) based on seasonal evapotranspiration for grain production was not significantly affected by irrigation system. However, WUE based on amount of irrigation water applied increased with decreases in amount of water applied.

Table 9. Average precipitation and irrigation water applied, and average runoff, soil water change, grain yield, evapotranspiration, and water use efficiency as affected by various water management systems for sorghum at Bushland, Texas, 1979-1981 (from Stewart et al., 1983).

System	Prec.	Irrig.	Runoff	Soil water depletion†	Grain yield	ET‡	Water use eff.§ Seasonal ET	Applied irrig.
	mm				Mg ha^{-1}	mm	kg grain m^{-3}	
Dryland	250	0	30	74	2.53	295	0.84	—
Dryland, diked	250	0	7	64	2.42	308	0.76	—
Fully irrigated	250	516	177	30	7.24	619	1.17	0.92
LID—high irrig.	250	233	9	45	5.69	520	1.08	1.36
LID—med. irrig.	250	174	5	46	5.13	466	1.09	1.70
LID—low irrig.	250	119	11	52	4.47	411	1.08	1.50
LSD—0.05 level	—	—	—	—	0.71	47	0.20	0.64

†Determined gravimetrically to a 1.8-m depth.

‡ET = Prec. + Irrig. - Runoff + Soil water depletion.

§Water use eff. = Grain yield (Mg ha^{-1} × 1,000) ÷ ET (mm × 10).

(Note: Data are from original publication. Slight differences between published values and values as calculated are due to rounding.)

Water use efficiency was 0.92 kg m^{-3} for the fully irrigated treatment and 1.70 kg m^{-3} for the LID system with the low level of irrigation. Improved yield responses with the LID system were attributed to virtual elimination of runoff, both from precipitation and irrigation. Besides greatly reducing runoff, the potential for soil loss was greatly reduced also.

Vertical Mulching

Water infiltration into Vertisols often is very low, which results in limited soil wetting, especially in low rainfall regions. Some practices have enhanced infiltration by retaining water on the land, thereby providing more time for infiltration. Another practice that enhances infiltration is vertical mulching, provided the mulched slot extends to the soil surface. Rao et al. (1978) evaluated vertical mulching at 2-, 4-, and 8-m spacings and obtained average increases of 45% in grain and 38% in straw yields of sorghum as compared to the control (no mulch) treatment. Increases were greater in dry than in wet years. A spacing of 4 m was found to be ideal for both wet and dry years.

Drainage

The emphasis in foregoing sections has been on soil and water conservation, but too much water also can be detrimental to crop production due to flooding and poor drainage. Where drainage is necessary, water must be conveyed from the field at nonerosive velocities.

For fields with nonuniform slopes, rows should drain into low catchment areas for retention or into field waterways for disposal. Low areas can be drained by connecting ditches that discharge into established waterways or ponds. For nearly level fields on Vertisols, surface drainage has been improved by using systems of beds and furrows, which provide drainage of the seed zone and result in higher yields (El-Swaify et al., 1985; Gupta et al., 1979; Kampen et al., 1981; Krantz et al., 1978). Yield increases up to 100% have been obtained, depending on rainfall amount and distribution. Planting on beds to improve drainage was recommended also by Bradfield (1969) for an intensive cropping system under high-rainfall conditions in the Philippines. Besides providing drainage during high-rainfall periods, the bed and furrow system also reduces runoff and soil losses, as reported by Pathak et al. (1985) for a study on a Vertisol in India (Table 10). Runoff with the bed and furrow system was about one half of that without the beds and furrows. The reduction in soil loss was even greater than the reduction in runoff.

SUMMARY

Although Vertisols occupy only about 1.8% of the world's land surface, they are important agricultural soils. Vertisols, however, are highly subject to erosion by water because of their low infiltration rates and their frequent occurrence on sloping soils. Wind erosion also may occur on Vertisols. Consequently, soil conservation is a major problem on Vertisols. Water conserva-

Table 10. Effects of land management systems on average annual runoff and soil loss from a Vertisol in India, 1975-1980 (from Pathak et al., 1985).

Treatments	Rainfall	Runoff	Soil loss
	mm	% of prec.	Mg/ha
Broadbed and furrow at 0.6% slope	810	14	1.17
Broadbed and furrow at 0.6% slope with field bunds	808	9	0.58
Broadbed and furrow at 0.4% slope†	853	11	0.86
Flat on grade at 0.6% slope	812	18	1.35
Traditional flat, monsoon fallow	806	27	6.64

†Average data for 1975-1978.

tion frequently also is a problem on Vertisols because they often occur where inadequate precipitation limits crop yields.

A permanent cover of grasses or trees would control erosion and conserve water on Vertisols, but such cover is not compatible with field crop production. Consequently, tillage systems and support practices are relied on for soil and water conservation. Conservation tillage practices, which maintain surface residues, are effective for conserving soil and water, provided adequate amounts of residues are available. Where residues are limited or used for other purposes and where conservation tillage is not used, properly used clean tillage practices can conserve soil and water. However, even greater soil and water conservation generally is possible when support practices such as contouring, terracing, stripcropping, furrow diking, etc. are used in conjunction with clean tillage. Under some conditions, drainage of excess water from the land at nonerosive velocities may be needed for more effective crop production. The particular type of soil and water conservation practice most appropriate for a given situation will depend on such factors as land slope, crops grown, and precipitation amount and distribution. However, equipment and other resources available to the producer, as well as the managerial ability of the producer, will strongly influence which crop production system is used in a given situation.

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